UPDATE APPROACHES AND METHODS FOR DIGITAL BUILDING MODELS – LITERATURE REVIEW

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SUMMARY: *A combination of systematic and bibliometric literature review is applied. For bibliometric analysis a citation network analysis, keyword cluster analysis, burst detection analysis and the total citation score are evaluated. So far, literature mainly deals with creation of digital building models. However, in the operational phase of a building, updating digital building models is essential in order to use the digital building models for applications like maintenance, facility management and conversion planning. In this paper approaches and methods to update digital building data are examined systematically to reflect the current state of scientific knowledge. This will identify and compare update approaches for digital building models. Nine interrelated research areas can be identified that deal with updating digital building information. Based on the body of knowledge on the topic "Updating of digital building models", research gaps and poorly represented research areas are identified. One gap in research is the use of photogrammetry to update individual buildings during their operational phase. In addition to strong research areas such as geoscience, which has produced update approaches over the years, areas like factory planning have been identified which hardly consider approaches to updating as-built data. Only the most important and largest research areas involved have been considered. A more detailed examination would be possible, but would go beyond the scope of this paper. This paper is the first to analyse updating approaches in a detailed, systematic, and bibliographic manner. The holistic view of the topic of updating approaches of digital building models helps to get an overview of existing approaches. Especially because in building operation up-to-date digital plan documents of the building are increasingly needed, this overview is necessary.*

KEYWORDS: *BIM (Building Information Modeling), Digital building model, Existing buildings, Laser scanning, Photogrammetry, Point cloud, Scan-to-BIM, Update, Updating*

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1. INTRODUCTION

With the development of digital building models, knowledge sharing between all stakeholders of construction or operating phase of a building has become possible. The use of building information modeling (BIM) technology in the design, construction and operating phases of buildings is increasing (van Berlo und Krijnen 2014). Using digital building models beyond the design and construction phase into the operating phase has been recognized. Benefits for facility management of buildings in order to facilitate tasks such as maintenance are evident.

However, the fact of current Architecture, Engineering, Construction and Operations (AECO) industry practice is that the updating of digital building models rarely is addressed during the life cycle of a building (Akcamete et al. 2009). Due to a buildings decades lasting lifecycle and changing occupants, tenants, residents and proprietaries buildings are refurbished, retrofitted, remediated or modernized. During their lifecycles, different building elements and products are installed, removed or changed in the course of building modification. Often, these modifications of the building structure, equipment and fittings are not documented properly (Volk et al. 2015). Also mostly the acquisition of building information of existing buildings is associated with expensive equipment and great acquisition and modelling effort of skilled staff. Here it makes no difference whether a digital building model already exists and needs to be updated or a new digital building model has to be created from scratch. This fact results in digital building models being wasted where they have the most value, in the operating phase. Thus, approaches of updating in form of installations, changes, or removals of one or more elements of the building structure, equipment and fittings have to be examined.

A literature analysis is to provide information on existing approaches of updating digital building models. Up to now, because of the overwhelming number of different approaches, it is hard to keep an overview and to see the differences, and, more importantly, the similarities of the methods. In addition, with the structure of the literature review, a new methodology is used to conduct a comprehensive literature review. This combines the advantages of a systematic literature review (SLR) and a bibliometric literature review (BLR).

2. BACKGROUND OF DIGITAL BUILDING MODELS

A component of every update is the recording of the current building situation, the so-called as-built condition. Various recording techniques can be applied when surveying buildings (see Fig. 1). Depending on the required LoD (Level of Development), the available budget and time, the size and complexity of the building, environmental and weather conditions, desired degree of automation and processable file sizes and formats, the appropriate surveying technology has to be chosen (Volk et al. 2014). Figure 1 first distinguishes between non-contact techniques and contact techniques. The non-contact techniques are divided into image-based techniques, range-based techniques, manual techniques, Global Positioning System (GPS) and data capturing techniques (Volk et al. 2014; Donath 2009; Busen et al. 2015). In the case of image-based techniques (Fig. 1) photogrammetry industry had advances in technology which led to a progressive digitalization in photography and photogrammetry applications. The development of image processing software has benefited and led to improvements of processing time and quality (Galantucci und Fatiguso 2019). Videogrammetry is of the same functionality as photogrammetry but takes video streams as the input data instead of a collection of images (Wang et al. 2019; Brilakis et al. 2011). Both technologies can be applied on construction sites, construction work, construction equipment and for surveying of existing buildings.

Among the range-based and more established recording techniques are laser scanning and measuring. Besides terrestrial laser scanning, mobile laser scanning methods are increasingly used. Especially in the recording of indoor building environments mobile laser scanning provides a platform for a variety of applications (Y. Cui et al. 2019). Tachymetry is a classical measuring method for determining the position and elevation coordinates of a terrain point by simultaneously measuring distance, horizontal direction and height difference with a tachymeter instrument. Thereby each new point is defined by polar coordinates, whereby the origin of the coordinate system is located in the instrument's standpoint. In modern total stations the tachymetric measurement technique is combined with laser equipment and is therefore assigned to laser measurement techniques. But it has to be mentioned that current total stations also rely on the use of image information during the measurement (Schäfer 2017)

BIM modeling (see Fig. 1), which is a manual technique, uses point clouds generated by laser scanning, photogrammetry or videogrammetry to support the modelling process of a BIM model. In addition, existing floor plans can be used to re-model existing buildings.

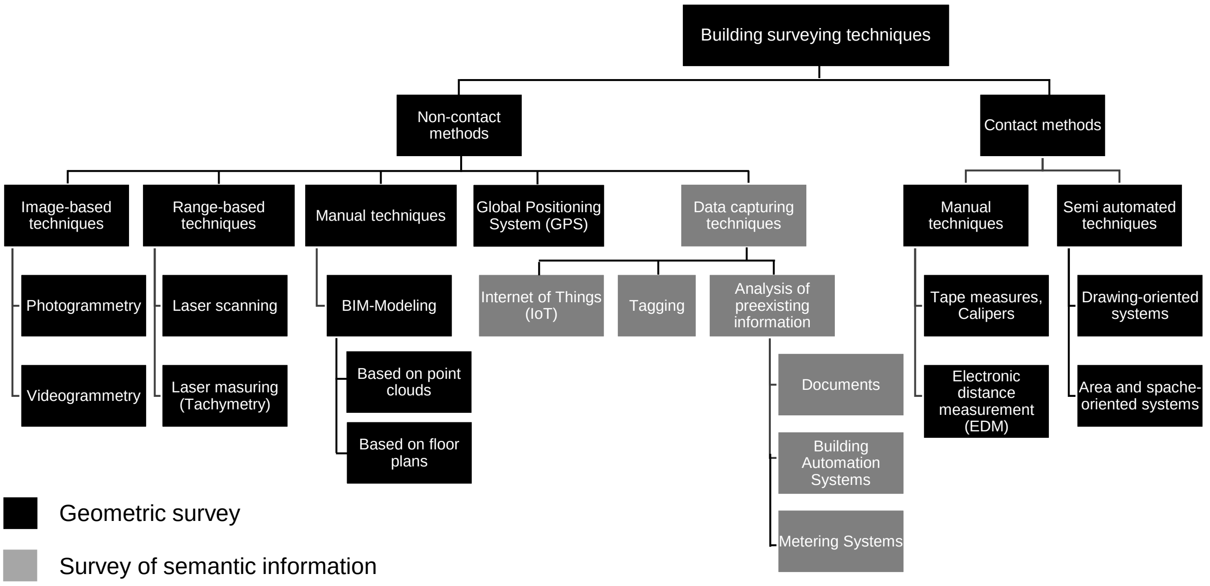

FIG. 1: Overview of surveying and data capturing techniques for existing buildings

Current approaches already aim at the partially automated and automated modelling of BIM models from point clouds. These approaches are summarised under the term scan-to-BIM (Fig. 2). The satellite-based positioning of the GPS (Fig. 1) is mainly used outdoors for building surveys (Donath 2009). Emerging applications as the implementation of high-rise building construction quality control based on GPS positioning technology are still applicable (Hui 2018). Data capturing techniques also belong to the "non-contact methods" and refer mainly to the acquisition of non-geometric information. Internet of Things-based (IoT) systems in commercial buildings support to monitor and fulfil the substantial requirements in terms of comfort, usability, security, and energy management (Minoli et al. 2017; Tang et al. 2019; Dave et al. 2018). The data capturing technique tagging describes labeling points to apply a standard metadata schema. Tagging is currently moving from a manual process to an automated process (Mishra et al. 2020). Data analytics of digital building data in any form are becoming increasingly common and provide additional insights into the operational phase of buildings (Burak Gunay et al. 2019). The data acquisition techniques mentioned here are not exhaustive. Contact techniques as direct distance measurement with tape or with additional equipment like EDM's (Electronic distance measurement) are determining the length between two points based on manual effort. These manual techniques can be partially automated by computer-aided applications (Donath 2009). Semi-automated techniques combine manual measurement procedures with software-supported data processing (cf. Fig. 1) (Donath 2009). Overall, manual techniques are being used far less frequently. Based on the mentioned techniques for building surveying and data acquisition, digital building models are created and enriched with information.

Not all of the recording techniques mentioned in Figure 1 are suitable for creating a digital 3D building model. Manual techniques (cf. Fig. 2) refer to manual modeling activities when creating digital building models, e.g., Building Information Modeling. Digital building models differ in the way they are created (see Fig. 2). A distinction can be made between image-based techniques, range-based techniques and manual techniques. Which technique is applied for a specific building depends on the available time, the available hardware and the subsequent purpose of use. The method of creation determines whether in the end a point cloud or a BIM model is needed (see Fig. 2). As described in the previous section, photogrammetric models are based on images and can also be converted into point clouds for further use (Tuttas et al. 2014; Masiero et al. 2019). When creating the images in the construction area techniques are distinguished by the different camera handling: handheld camera, aircraft carried camera (also UAV (unmanned aerial vehicle)), crane-mounted camera and cameras on AGVs (Automated guided vehicle). Laser scanners generate point cloud models of the geometry of a building (cf. Fig. 2) and enable fast and high quality building surveys to represent the actual building (Mahdjoubi et al. 2013). For some real estate services, point clouds are completely sufficient and the time-consuming creation of BIM models can be avoided. Some approaches also combine point cloud models and photogrammetry models (Fawzy 2019). BIM models for example can be used to support facility management processes (Becerik-Gerber et al. 2012), performance analytics (Han und Golparvar-Fard 2017; Jin et al. 2019), to coordinate planners and processes (Steinmann et al. 2016) or to enable sustainable building design processes (Zanni et al. 2017). However, the manual effort to create a BIM model is very high and even grows with increasing LoD (Leite et al. 2011). Although there are already efforts to create BIM models automatically based on point clouds (scan-to-BIM) (Czerniawski und Leite 2020), these approaches are rarely used in practice. Therefore, the creation of BIM models in Figure 2 is still considered a manual technique.

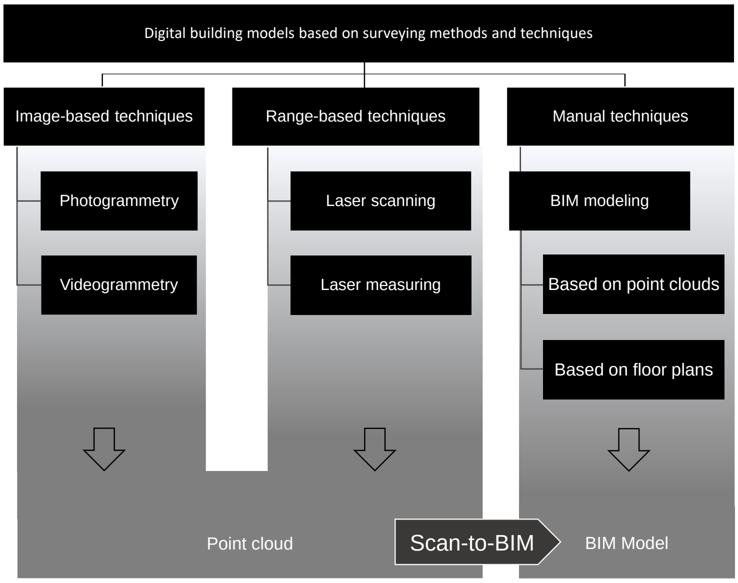

FIG. 2: Types of digital building models based on the creation technique

In order to be able to use digital building models in existing buildings for applications such as the provision of information during conversion processes or for maintenance, the building model must be up-to-date during operation. Thus, a main distinction is made between new buildings and existing buildings (cf. Fig. 3). For new buildings, the planning status during the planning and construction phase is called "as planned" building model. A digital building model is used in the planning phase, e.g., to quantify required building materials, coordinate subcontractors and visualise the planned building (Kreider und Messner 2013). For existing buildings, a distinction is made between two cases: a pre-existing digital building model is available and no digital building model is available (cf. Fig. 3).

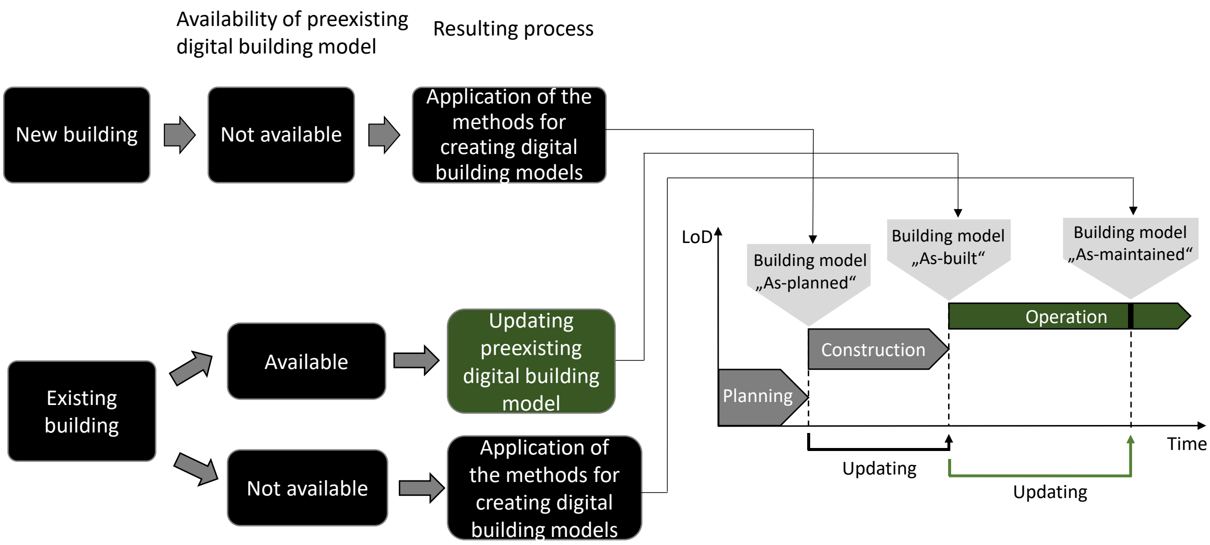

FIG. 3: Distinction between creation or update processes for new and existing buildings

In case of an existing digital building model the as-built model has to be updated to the state of the as-maintained model. When the digital building model is completely rebuilt, the as-maintained state is created directly (cf. Fig. 3). Existing buildings which already feature a digital building model mostly provide incomplete, outdated or fragmented digital building models (Lu et al. 2020; Becerik-Gerber et al. 2012). Missing or obsolete building information negatively affect project management, lead to uncertain process results and time loss or cost increases in maintenance, conversion or remediation processes. As existing buildings often lack "as built" and "as maintained" documentation (Fig. 3) due to omitted updating, limitations of digital building model use in existing buildings are expected (Cui et al. 2019). It can even be assumed that no digital building model exists for older buildings. The field of research on updating digital building models of existing buildings has been neglected so far, despite obvious problems during the operation phase of buildings (Volk et al. 2014). This article will examine and introduce the approaches and developments of updating efforts of digital building models. The phase of interest is the operation phase (cf. Fig. 3) of existing buildings. Other, related fields of research, such as geoscience, are also examined for possible solutions with regard to updates. Subsequently, strong and weak research fields are identified and research gaps are concluded.

3. RESEARCH METHODOLOGY

To achieve the answer of following research question:

- Which update approaches and methods are existing for digital building models?

A two-pronged methodology is undertaken to compile the literature of updating approaches for buildings (cf. Fig. 4). This methodology is a combination of a systematic literature review (SLR) and a bibliometric literature review (BLR). The proposed methodology is an extension of the Systematic Literature Network Analysis (SLNA) which was proposed by Colicchia & Strozzi (Colicchia und Strozzi 2012). The proposed research methodology in Figure 4 combines the SLR (Tranfield et al. 2003; Ben Rjab und Mellouli 2019) to define the research aim and to perform a first selection of the most relevant studies to be included in the analysis. Followed by a BLR (Li et al. 2017; van Eck und Waltman 2014) in order to perform an analysis on a data base extraction to investigate the process of knowledge creation, transfer and development (cf. Fig. 4). After the literature database (2), (see Fig. 4) and the specific search term (3) have been determined, based on the research question (1) the inclusion and exclusion criteria are defined (4). Then a CSV file is exported, which is used for the analyses in the BLR. The first block of the BLR, the citation network analysis (CNA) including the main path, helps to analyse the literature and to understand how the body of knowledge has evolved over time (Zhao und Strotmann 2015).

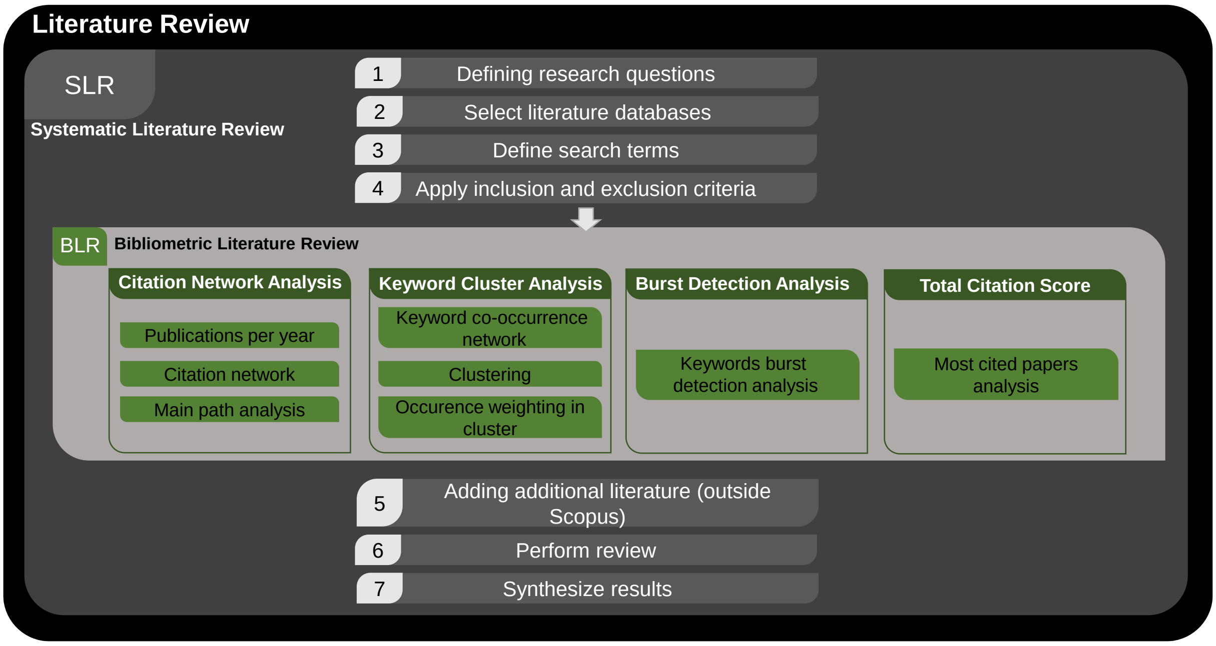

FIG. 4: Research methodology overview

In the next section the keyword cluster analysis shows with what frequency the keywords occur and what connections exist between the individual fields of research (Chen et al. 2016). A network of keywords offers an extensive picture of a knowledge domain, providing an understanding of the existing research interests, and how they are intellectually connected and organized. This analysis is followed by the burst detection analysis which shows the chronological progression of the trends and their strength (Chen 2006; Mane und Börner 2004). Citation bursts illustrate which keywords have been frequently cited within the literature in a particular time period, notably fast-growing topics, or topics that are associated with surges in citations (Strozzi et al. 2017). This allows current research trends to be identified. The last step of the BLR is the total citation score of the most cited papers. In the list of the most cited papers the most influential authors of the topic updating digital building models are listed. Finally, the identified literature is filtered, additional literature added and reviewed. The results can then be extracted. With the help of the presented research methodology (cf. Fig. 4) the research field of updating approaches of digital building models is outlined and analysed.

4. LITERATURE REVIEW

This section defines the foundations of a comprehensible and transparent literature analysis. The SLR (steps 1-4), the BLR and then the SLR (steps 5-7) are carried out (cf. Fig. 4).

4.1 Systematic literature review (steps 1-4)

The SLR identifies, selects and critically appraises research in order to answer the formulated research question. Therefore, the SLR provides a comprehensive, transparent conducted search over the database of Scopus that can be replicated and reproduced by other researchers. Based on the research question, the literature database and the specific search term are determined. Then, in order to reduce the number of documents with regard to relevance, inclusion and exclusion criteria are selected.

The first phase is represented by the definition of the scope of the study. Hence, in this research, it is aimed to understand: Which update approaches and methods are existing for digital building models? Based on the research question, the SLR and BLR is conducted. In this way a step-by-step approach towards the body of knowledge is achieved (cf. Fig. 4).

The literature database Scopus was chosen as data source. Prerequisite for suitable literature database was that the results should be exportable as a CSV file. Furthermore, Scopus was identified as a suitable data source for the complex topic of the research question. The selection is based on the comparison between Scopus and Web of Science from 2016, which compares the two databases based on Ulrich's directory (Mongeon und Paul-Hus 2016). In the field of engineering, Scopus was, the data source that covers more literature. In addition to engineering, the areas of biomedicine, social sciences, arts and humanities were also compared. Due to the high literature coverage of Scopus and the resulting high number of documents, it was chosen not to search further databases and to combine the CSV files.

To search for documents, the following search query was used in the database Scopus, as in the previous section explained: TITLE-ABS-KEY ("Construction site" OR "BIM" OR "Building Information Modeling" OR "Building Information Modelling" OR "Point Cloud" OR "Digital building model" OR "Digital building Twin" OR "factory planning" OR "factory Building" OR "Photogrammetry" OR "Photogrammmetry" OR "LIDAR" OR "laser scanning" AND ("Update" OR "Updating")). To get the desired results with the research focus on point clouds and BIM models (Fig. 2) these terms were integrated into the search string and synonyms were placed. In addition, general digital building models, the construction industry and factory planning where current models are relevant have been added by the keywords "construction site", “factory planning/building". Thus, possible update approaches from different application areas can be identified by combining them with the terms "update" and "updating". The search term used attempts to identify all documents that contain solutions for updating digital data sets of building information or similar constructions. After applying the search term, the search returns 1965 documents. Further inclusion and exclusion criteria are needed to limit the results and to focus on update approaches in the construction sector.

In the following, the inclusion and exclusion criteria, which are used to specify and limit the search results, are presented. The inclusion criteria are (cf. Fig. 5): Period of publication: 2000-2020; Document type: Conference paper, article; Language: English. Excluded from the search were the following topics: Chemistry, medicine, health professions, neurosicience, pharmacology, dentistry, nursing, psychology and veterinary. These topics had previously provided results, but without relevance to the actual topic of updating building models. Furthermore, publications in the "article in Press" stage were excluded to have only completely elaborated research results available. This reduced the number of documents to 1572. These 1572 documents are exported as CSV files and used for the BLR.

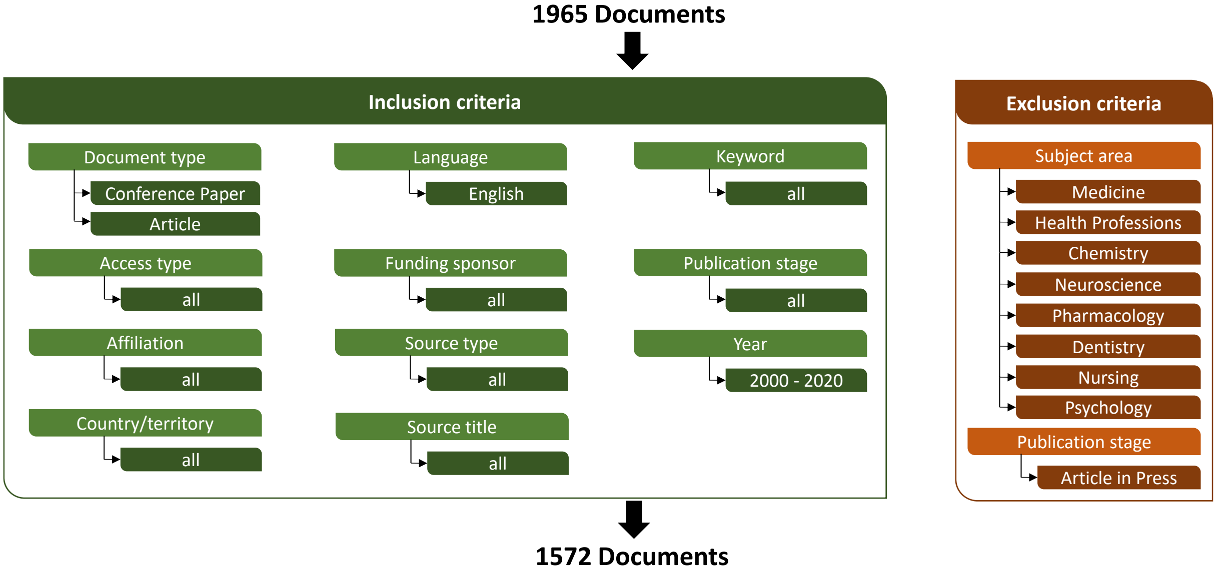

FIG. 5: Overview of inclusion and exclusion criteria

The search string with inclusion and exclusion criteria is: TITLE-ABS-KEY ("Construction site" OR "BIM" OR "Building Information Modeling" OR "Building Information Modelling" OR "Point Cloud" OR "Digital building model" OR "Digital building Twin" OR "factory planning" OR "factory Building" OR "Photogrammetry" OR "Photogrammmetry" OR "LIDAR" OR "laser scanning" AND ("Update" OR "Updating")) AND (EXCLUDE (PUBYEAR , 2021) OR EXCLUDE (PUBYEAR , 1999) OR EXCLUDE (PUBYEAR , 1998) OR EXCLUDE (PUBYEAR , 1997) OR EXCLUDE (PUBYEAR , 1996) OR EXCLUDE (PUBYEAR , 1995) OR EXCLUDE (PUBYEAR , 1994) OR EXCLUDE (PUBYEAR , 1993) OR EXCLUDE (PUBYEAR , 1992) OR EXCLUDE (PUBYEAR , 1991) OR EXCLUDE (PUBYEAR , 1990) OR EXCLUDE (PUBYEAR , 1989) OR EXCLUDE (PUBYEAR , 1988) OR EXCLUDE (PUBYEAR , 1987) OR EXCLUDE (PUBYEAR , 1986) OR EXCLUDE (PUBYEAR , 1985) OR EXCLUDE (PUBYEAR , 1984) OR EXCLUDE (PUBYEAR , 1983) OR EXCLUDE (PUBYEAR , 1982) OR EXCLUDE (PUBYEAR , 1981) OR EXCLUDE (PUBYEAR , 1980) OR EXCLUDE (PUBYEAR , 1977) OR EXCLUDE (PUBYEAR , 1976) OR EXCLUDE (PUBYEAR , 1975) OR EXCLUDE (PUBYEAR , 1973) OR EXCLUDE (PUBYEAR , 1970)) AND (EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "PSYC") OR EXCLUDE (SUBJAREA , "VETE")) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (PUBSTAGE , "aip")) AND (LIMIT-TO (LANGUAGE , "English"))

4.2 Bibliometric literature review

After the first steps of the SLA and, thus, a preselection of literature, the BLR follows. The exported CSV file is the starting point for the following bibliometric analyses. The CSV file includes authors, document title, year, source title, volume, issue, pages, citation count, source, document type, author keywords, index keywords and the references of the included papers. This provides the necessary information for the bibliometric analysis.

4.2.1 Citation network analysis (CNA)

In the first step the CNA is carried out (Fig. 4). The general aim of the CNA is to show the process of creation and transfer of knowledge through scientific publications. The collective view of a large number of citing authors regarding the relationships between documents represented by citations, which is the citation network, can therefore be analysed to study the intellectual structures of research fields, and to inform knowledge organization and information retrieval (Zhao und Strotmann 2015). By making comparisons between time periods, the historical development of the research field of updating digital building models is studied. This clearly shows the current state of science.

In the following, the number of publications per year is analysed to understand the research interest in the subject area of updates (Fig. 6). The documents numbers are distributed over time as shown by Figure 6, revealing an increasing interest into the topic in the last decade, especially in the last six years. A first strong increase in the number of documents can be observed between the years 2003 and 2004. While in 2003 the publications were mainly in the field of Geographic Information System (GIS) and city modeling (Astori et al. 2012; Müller et al. 2003; Wu et al. 2003), in 2004 the updating of individual buildings (Knudsen und Nielsen 2004) or infrastructure structures (Zhang und Couloigner 2004) as well as change detection (Vu et al. 2004) has moved into the research focus. This change of topic was accompanied by an increase in publications.

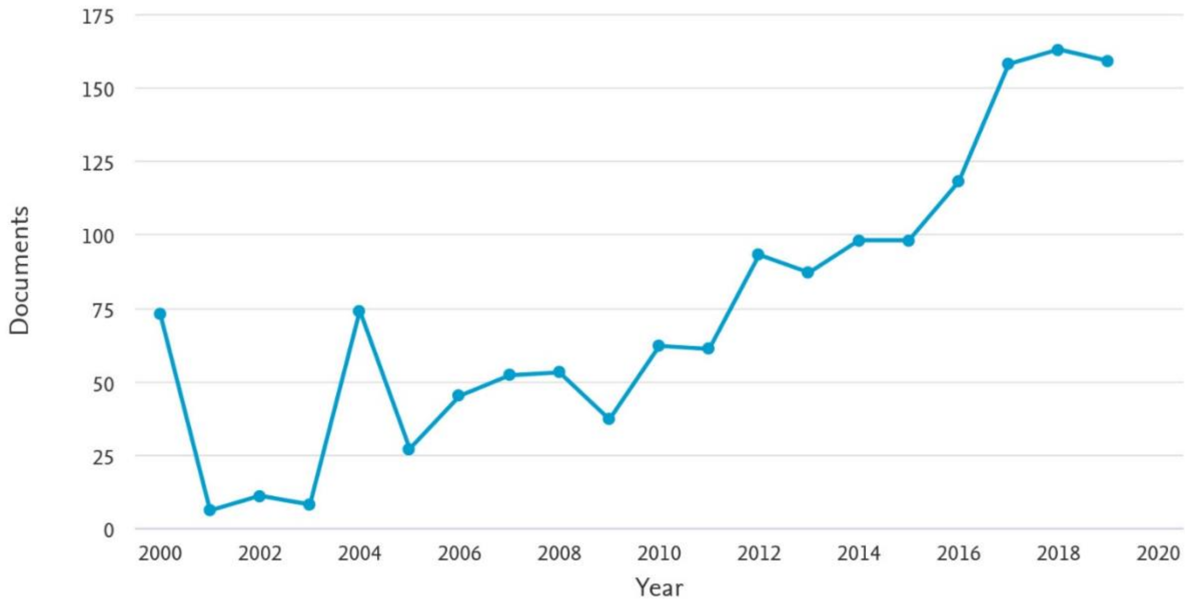

FIG. 6: Documents by year about updating approaches of digital building models

Starting in 2005 (27 publications) the number of publications per year increased almost continuously to 163 publications in 2018. During this period, new fields of research such as the updating of construction sites (Yu et al. 2018), BIM models (Khodeir und Nessim 2018), approaches from robotics (Zhang et al. 2017) and localization and mapping (SLAM) approaches (Andert et al. 2017) have been established, which have significantly increased the number of publications.

This is followed by an examination of the citation network (Fig. 7). A citation network is a way of organising and representing the literature using cited references. Collaboration of the authors and the generated flow of knowledge becomes visible in a citation network. When authors cite one another, they show connections between published papers, and, therefore, connections between the ideas those papers represent. An author implies a subject relationship to a paper when they cite it. An arrow represents a quotation. The direction of the arrow indicates who is quoted by whom (Fig. 9). The arrow always goes from the cited paper to the paper that quotes it. Of the 1572 documents, Figure 8 lists the clusters (1-50) that are linked to each other. The extraction of the cluster distribution, citation network (cf. Fig. 7) and main path (cf. Figs. 9-12) was performed using the Pajek software for large network analysis (Batagelj und Mrvar 1998). In total, 733 publications linked by citations can be identified. These form 50 clusters (see Fig. 8). The largest clusters are cluster 1 with 74 related publications, cluster 5 with 12 associated publications, cluster 10 with 30 related documents and cluster 16 with 15 related publications. The overall citation network is presented in Fig. 7 to highlight the largest clusters and to evaluate their research content in the main path analysis. Unconnected elements are aligned in a circle and connected components were positioned in the middle (see Fig. 7). In the citation network (cf. Fig 7) of the set 1572 papers, many nodes are isolated, but there are also connected components (cf. Fig. 8): the biggest connected component includes 74 papers, the second biggest includes 30 papers, the third largest connected component consists of 15 documents and the fourth biggest linked cluster includes 12 publications. The other clusters include 2 to 7 papers each (cf. Fig 8).

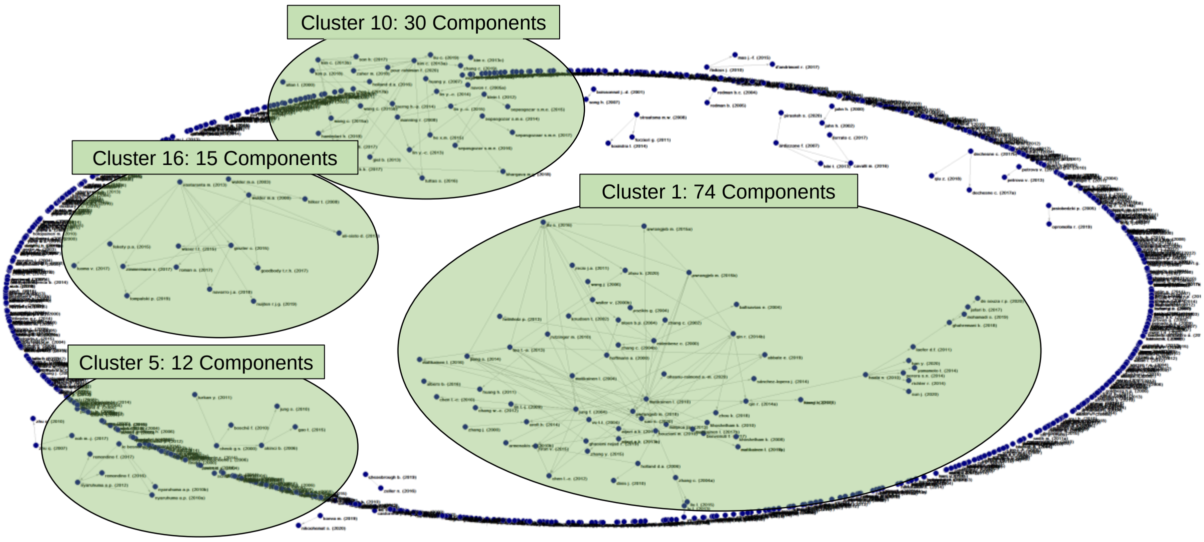

FIG. 7: Citation network

1. Weak Components of N2 [>=2] (1000, comp.=53)

Dimension: 1000
The lowest value: 0
The highest value: 53

Frequency distribution of cluster values:

Cluster	Freq	Freq%	CumFreq	CumFreq%	Representative
0	733	73.3000	733	73.3000	delgado r. (2015)
1	74	7.4000	807	80.7000	cao s. (2020)
2	5	0.5000	812	81.2000	pirasteh s. (2020)
3	2	0.2000	814	81.4000	hedrick a.r. (2020)
4	2	0.2000	816	81.6000	blinder d. (2020)
5	12	1.2000	828	82.8000	alshaiba o. (2020)
6	2	0.2000	830	83.0000	nikoohemat s. (2020)
7	3	0.3000	833	83.3000	chiang k.-w. (2020a)
8	5	0.5000	838	83.8000	lombard c.d. (2020)
9	2	0.2000	840	84.0000	soti r. (2020)
10	30	3.0000	870	87.0000	pour rahimian f. (2020)
11	4	0.4000	874	87.4000	colucci e. (2020)
12	3	0.3000	877	87.7000	liu d. (2020)
13	2	0.2000	879	87.9000	cheng y.-j. (2019)
14	2	0.2000	881	88.1000	sun y. (2019)
15	2	0.2000	883	88.3000	li y. (2019)
16	15	1.5000	898	89.8000	tompalski p. (2019)
17	2	0.2000	900	90.0000	bautista-de castro á. (2019)
18	3	0.3000	903	90.3000	sayer a.m. (2019)
19	2	0.2000	905	90.5000	chen k. (2019)
20	2	0.2000	907	90.7000	tran h. (2019)
21	2	0.2000	909	90.9000	radulović a. (2019)
22	2	0.2000	911	91.1000	liu k. (2019)
23	2	0.2000	913	91.3000	opromolla r. (2019)
24	2	0.2000	915	91.5000	chesebrough b. (2019)
25	2	0.2000	917	91.7000	chen z. (2018)
26	7	0.7000	924	92.4000	puniach e. (2018)
27	3	0.3000	927	92.7000	xu h. (2018)
28	3	0.3000	930	93.0000	qiu z. (2018)
29	3	0.3000	933	93.3000	barrile v. (2018)
30	3	0.3000	936	93.6000	ni d. (2018)
31	4	0.4000	940	94.0000	singh u.n. (2017)
32	3	0.3000	943	94.3000	noh m.-j. (2017)
33	4	0.4000	947	94.7000	d'andrimont r. (2017)
34	6	0.6000	953	95.3000	remondino f. (2017)
35	2	0.2000	955	95.5000	kim m.-k. (2016)
36	3	0.3000	958	95.8000	kolzenburg s. (2016)
37	2	0.2000	960	96.0000	oliveira m. (2016)
38	2	0.2000	962	96.2000	kang z. (2016)
39	2	0.2000	964	96.4000	wu s. (2016a)
40	2	0.2000	966	96.6000	holland d.a. (2016)
41	2	0.2000	968	96.8000	lee j. (2016)
42	4	0.4000	972	97.2000	towers p. (2016)
43	6	0.6000	978	97.8000	gao t. (2015)
44	2	0.2000	980	98.0000	zhang c. (2015)
45	2	0.2000	982	98.2000	he x.m. (2015)
46	3	0.3000	985	98.5000	kooistra l. (2014)
47	2	0.2000	987	98.7000	poppenga s.k. (2013)
48	3	0.3000	990	99.0000	duro d.c. (2013)
49	2	0.2000	992	99.2000	petrova v. (2013)
50	2	0.2000	994	99.4000	song h. (2007)
51	2	0.2000	996	99.6000	kressler f.p. (2005)
52	2	0.2000	998	99.8000	redman b. (2005)
53	2	0.2000	1000	100.0000	jahn h. (2002)
Sum	1000	100.0000			

FIG. 8: Cluster distribution and number of containing documents

Considering only the four biggest connected components, it was extracted the key-route main path in order to visualize the knowledge diffusion path. Thus, the four most important thematic developments within the update research area can be identified and analysed.

The four main path analyses provide information on the current status within the individual research fields in the four sub-areas. To create the main paths, subnetworks were extracted from the overall network.

Mainpath: Geoscience

The largest cluster consisting of 74 publications is dealing with update approaches of geo-databases. It was chosen that the 11 most important (most cited) papers should be included in the main path. The 11 papers representing the main path nodes range from 2004 to January 2020, proving the recent development of the topic (cf. Fig. 9).

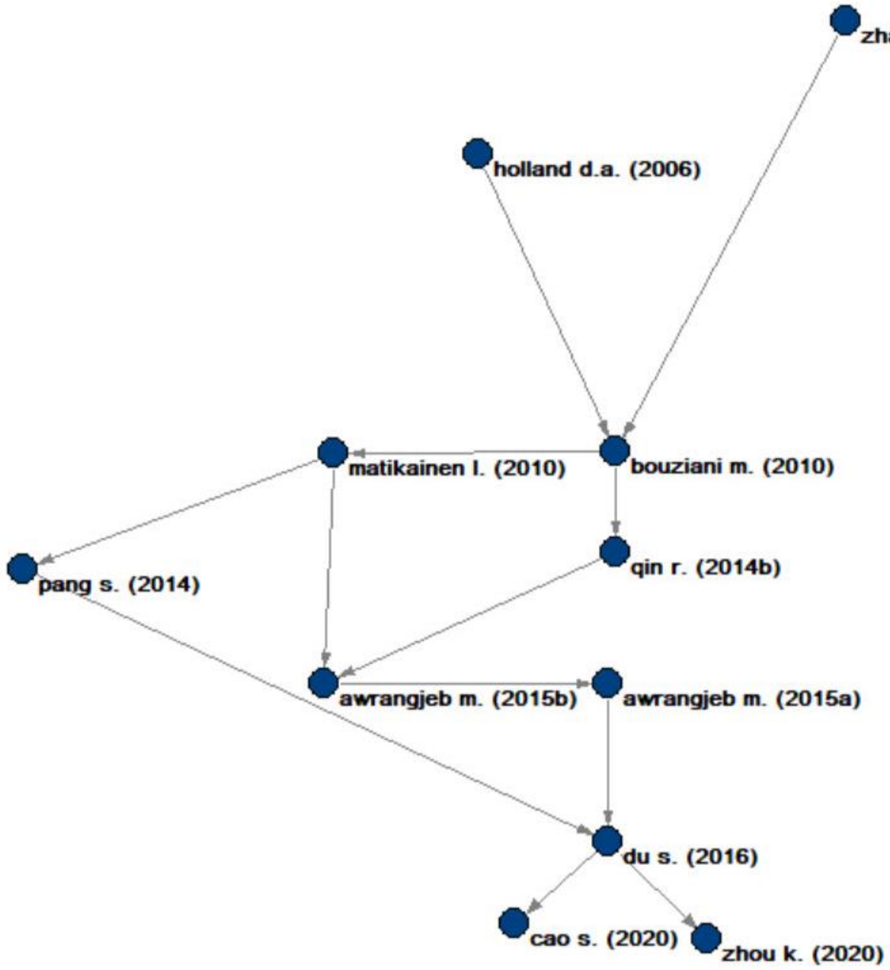

FIG. 9: Main path cluster 1

Parallel to the first drastical increase in 2004 (cf. Fig. 6) in the number of papers published, the main path (cf. Fig. 9) starts with a publication of Zhang (2004) providing an automated updating approach for road databases by the integration of imagery and geodata. This publication origins from the research field of geodesy and heralds the start of update approaches, even if they initially only concern infrastructure buildings. The impact of the publication is remarkable, with 94 citations, highlighting the research needs of updating approaches. Independently of this, Holland et al. (2006) proposed to update topographic mapping based on satellite images in Great Britain (cf. Fig. 9). The publications of Zhang (2004) and Holland et al. (2006) were taken up by Bouziani et al. in 2010 and used for the development of an automatic change detection focusing on buildings in an urban environment (Bouziani et al. 2010). The method is proposed as an update process for cartographic maps. Inspired by this and recognizing the strong interest in automated methods for updating map databases, Matikainen et al. (2010) compares different methods for recognizing buildings based on airborne laser scanner and digital aerial image data

(Matikainen et al. 2010). The publication of Pang et al. (2014), which takes up the findings of Matikainen, shows how closely change detection is related to the updating of digital building data. This study proposes an automatic method that applies object-based analysis to multi-temporal point cloud data to detect building changes. A milestone in the update of geo-database (Fig. 9) is set by Qin and Gruen (2014). For the first time mobile laser scanning is combined with terrestrial images to develop a cost-efficient method for frequent data updates. The high number of 64 citations illustrates the influence of the publication. In 2015, Awrangjeb published two publications with update approaches (see Fig. 9). In the first publication, Awrangjeb et al. (2015) developed a method to update the identified changes in the existing building map using a graphical user interface. The approach uses point clouds based on connected component analysis. The second publication by Awrangjeb (2015) highlights the savings of the proposed update method. It is pointed out that the proposed approach can be exploited for enhanced automated building information updating within a topographic database. Du et al. (2016) adopted Awrangjeb's approach to combine images and light detection and ranging (LiDAR) data and used the iterative closest point (ICP) algorithm. This achieves a change detection based on old aerial photographs and new LiDAR data. As in previous approaches, change detection is the basis for updating geo-databases. Current approaches to change detection of three-dimensional building changes are provided by Cao et al. (2020). Here, the focus is on the transition of multi-level change monitoring of urban buildings from 2D to 3D. This study presents a new automated Object–Grid–City Block 3D building change detection approach that entails the application of multi-temporal aerial LiDAR point clouds. The last publication in the mainpath for updating geo-databases comes from Zhou et al. (2020). Here the change detection is repeatedly highlighted as a prerequisite for updates. The paper proposes LiDAR-guided dense matching to address quality problems explicitly for detecting accurate building changes. Data sparsity and irregular spacing is addressed by densifying LiDAR points in a form of a digital surface model (DSM).

Mainpath: BIM

The second largest cluster consisting of 30 publications (Fig 7, Fig. 8) is dealing with update approaches of BIM models. It was chosen that the 13 most important (most cited) papers should be included in the main path. The 13 papers representing the main path nodes range from 2012 to 2020, proving the recent development of updating BIM models (cf. Fig. 10). The research field, which deals with the updating of BIM models, can be divided into three research streams: Construction progress monitoring, scheduling and geometry updating (cf. Fig. 10).

Construction progress monitoring

In 2013 Kim Changmin published a paper dealing with automated construction progress measurement. It is Kim's most successful publication from 2013 and has 139 citations (Kim, Son and Kim, 2013). It identifies that construction progress control is critical to the success of construction projects. The publication is limited to the construction phase and is based on the use of remote-sensing technology. Wang and Cho (2015) involve updating digital building models of existing buildings with energy efficiency applications. They introduce automatic as-is simplified BIM creation from point clouds for energy simulations. The publication of Han and Golparvar-Fard (2017) also refers to construction performance monitoring and investigates current strategies for using big visual data to document the as-built status. The paper begins with a literature review and then presents a method for localizing visual data in construction. The big influence and interest in the topic is evident in the 94 citations. Bhargava et al. (2018) uses the results of Han and Golparvar-Fard (2017) and Kim, Son and Kim (2013) and developed an extended approach to use the variety of data on construction sites for systematic documentation of construction processes (cf. Fig. 10) (Mandava et al. 2018). The approach is based on reliable, relevant and fast visual data analytics methods. Kim et al. (2018) inherits previous results and develops an approach to localizing mobile robots on construction sites. The resulting point clouds are additionally provided for several construction applications including defect management, safety, legal dispute, supply chain management and as-built BIM. Another approach for updating as-built BIM models is developed by Zhang (2019) (Zhang und Huang 2019). This is the first time artificial intelligence based on image processing is used in this context. The latest approach to monitoring and updating construction sites is that of Pour Rahimian (2020), (Fig. 10) (Pour Rahimian et al. 2019). The proposed framework leads to an automated update of the 3D virtual environment with states of the construction site. A integration of machine learning and image processing approach contributes to the body of knowledge of updating construction sites. Other approaches that deal with construction progress monitoring but are not included in the mainpath are (Gao et al. 2015; Amer und Golparvar-Fard 2018; Lin et al. 2019).

Scheduling

In 2013 Kim and Son released: Development of a System for Automated Schedule Update Using a 4D Building Information Model and 3D Point Cloud (cf. Fig. 10: Kim C. (2013a)). They focused on updating the schedule, which is closely linked to the BIM model. A publication by Kim, Kim and Kim (2013) focuses on the construction phase and developed an approach for updating a 4D CAD model using image processing (cf. Fig. 10: Kim C. (2013c)). Characterized by 3D CAD-based image mask filters, color-based noise removal, and area-based progress calculation, the image processing approach provides as-built schedule information. In 2014 Tserng et al. takes up the results of Kim, Son and Kim (2013) (cf. Fig. 10: Kim C. (2013b)) and develops a BIM-assisted schedule management system. For this purpose, Tserng et al. develoed a browser based as-built schedule. The branch of research culminates in a publication by Hamledari et al. in 2018 (see Fig. 10). This paper proposes a technique that uses the industry foundation classes (IFC) schema to automatically update an as-designed BIM based on site observations for inspected building elements. It receives as input an inspected object's actual type and inspection details including the detected defects/changes, responsible actors, as-built/as-is type, captured images, and time and the date of the inspection. The algorithm automatically analyses the IFC data model to retrieve the element's semantics and identifies discrepancies between the as-built/as-is and as-designed object conditions. This is the most sophisticated method for updating schedules in combination with BIM models.

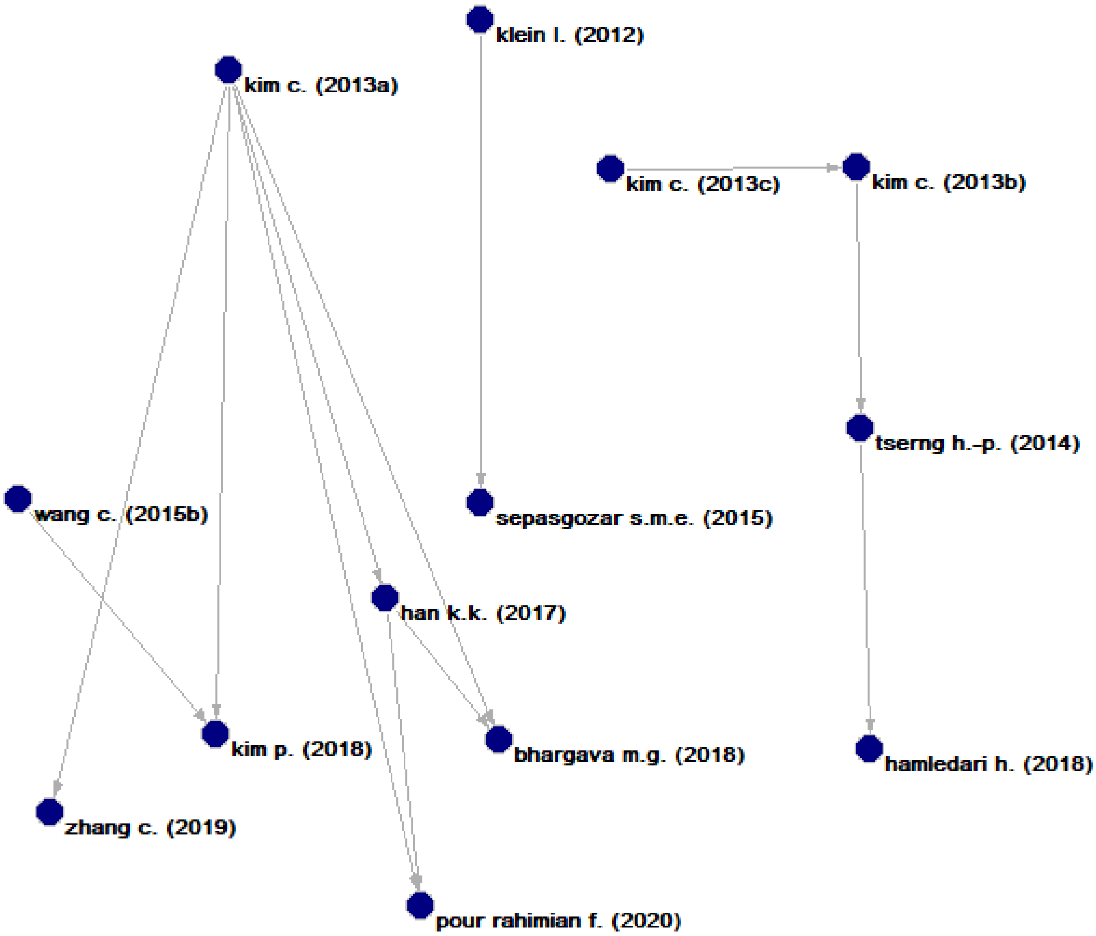

FIG. 10: Main path cluster 10

Geometry updating

The first publication of Klein et al. (2012) compared image-based and manually taken measurements (Fig. 10). The recordings were taken for verification of the as-built environment and updating procedures. Both techniques are compared in the end with an as-built BIM model as verification. This publication highlights that the need for up-to-date models for operations and maintenance purposes was recognized very early. In 2012, the publication revealed disadvantages in terms of accuracy of photogrammetry applications. Based on Klein et al. (2012), Sepasgozar et al. (2014) provide a LiDAR-based approach to create as-build models. This approach relies on manual modeling based on 3D point clouds. Due to the few publications on geometry updating, a underrepresented research stream can be identified in comparison to scheduling and construction progress control.

Mainpath: LiDAR forest inventory update

The cluster 16 (cf. Figs. 7 and 8) contains 15 publications and deals with LiDAR updating approaches. The most important publications range from 2003 to 2019 (cf. Fig. 11) and represent the knowledge development and knowledge flow of this subordinate research current. In 2003 Wulder and Seemann published a highly regarded (98 citations) publication on forest inventory height update through LiDAR. This publication led to another publication by Wulder et al. (2008) cited by 203 other researchers. It highlights the importance of LiDAR technology for sustainable forest management. In 2008 Hilker et al. proposed for the first time the combined use of LiDAR and satellite images to update forest inventory data. In forestry, too, change detection is directly linked to the updating of inventory data from Ali-Sisto and Packalen (2017). For this purpose, a comparison between 3D point clouds from aerial stereo images and LiDAR is performed (Ali-Sisto and Packalen 2017). The latest publication in this area by Tompalski et al. (2019) again combines analyses of point cloud data and photogrammetric data. For the approach, separate regression models were developed and compared that used the differences in point cloud metrics. The publications mentioned are representative of this research trend. Therefore, the remaining publications in this field will not be discussed further.

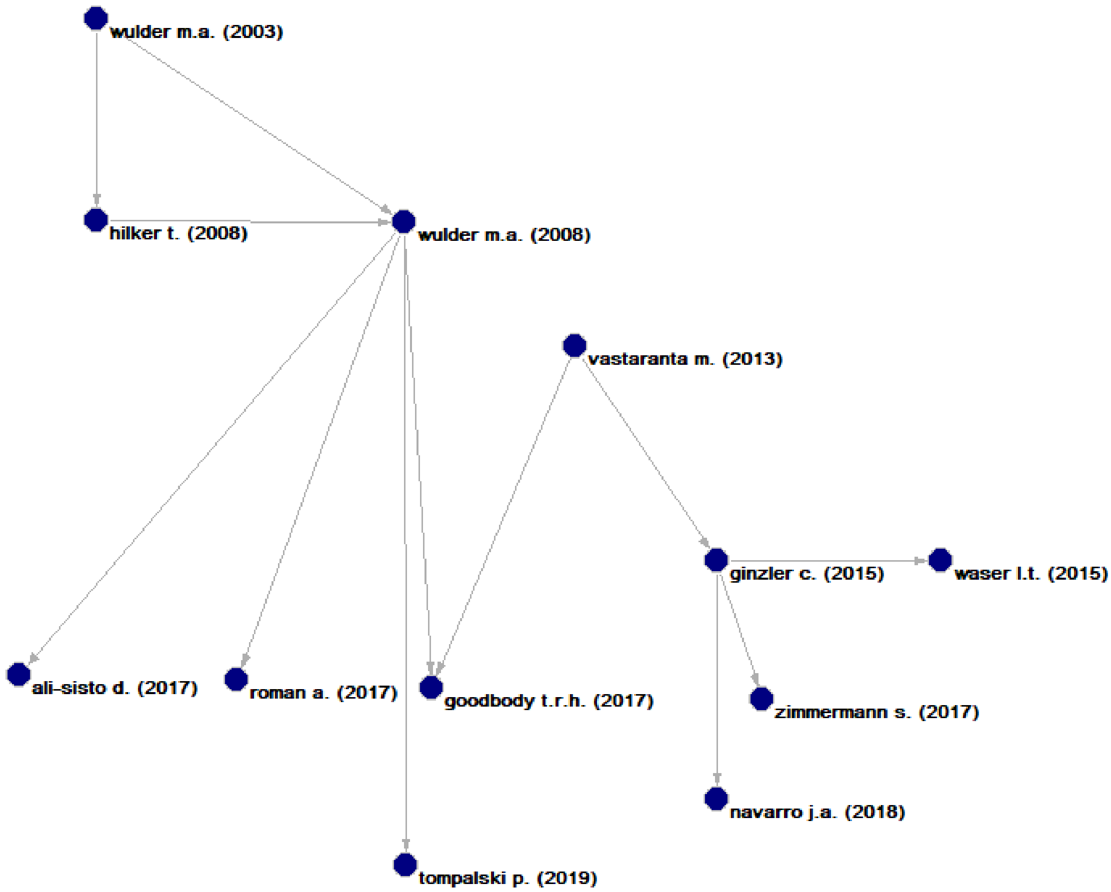

FIG. 11: Main path cluster 16

Mainpath: Updating cadastral maps via imagery and photogrammetry

The cluster 5 (cf. Figs. 7 and 8) contains 12 publications and is the smallest of the relevant clusters and deals with imagery and photogrammetry based updating of cadastral maps. The most important publications range from 2013 to 2020 (cf. Fig. 12) and represent the knowledge development and knowledge flow of this subordinate research stream. The first publication of Ali et al. (2013) deals with the update of cadastral maps based on remote sensing imagery from satellites. This study develops an integrated approach by integrating global position system (GPS) data, remote sensing (RS) imagery, and existing cadastral maps. In 2013 the paper of Cramer et al. gives a state-of-the-art report on the current activities and overall acceptance of remotely piloted airborne systems (RPAS) technology in European photogrammetric mapping. An approach that also uses LiDAR is that of Guan et al. (2015). Referring to the approach of Guan et al. (2015), Javanmardi et al. (2017) present the development of an automated object extraction strategy for rapid and accurate road marking inventory also based on mobile LiDAR. Alshehhi (2017) develops an approach for the extraction of streets and buildings based on remote sensing imagery with convolutional neuronal networks (cf. Fig. 12). One intended application is the updating of geographical databases. The publication of Alshehhi is pioneering and highly regarded with 115 citations. Akbulut et al. (2018) takes up the approach of Alshehhi (2017) (cf. Fig. 12) and uses not only images but also LiDAR data to automatically extract buildings. This approach also combines the advantages of the respective data sources: LiDAR point cloud and aerial imagery. Yang et al. (2018) also refers to the work of Alshehhi et al. (2017) (cf. Fig. 12) and is dedicated to updating geographic databases in urban planning. For this purpose, an approach is developed to extract buildings on high-resolution images. Starting in 2018, unmanned aerial vehicles (UAVs) are increasing used to create and update map material with highly accurate images. The work of Koeva et al. (2016) is representative for this development. The most recent developments are represented by the publications of Widyanigrum et Lindenbergh (2020), Abujayyab et al (2020) and Alshaiba et al (2020) (cf. Fig. 12). Widyanigrum amd Lindenbergh (2019) develop an approach for updating the road network automatically from airborne LiDAR point clouds combined with an aerial orthophoto. Abujayyab (2020) develops the first approach to create and update BIM footprints based on satellite images. Matlab software is utilized for machine learning and neural networks implemented for extracting the buildings' footprints (Abujayyab and Karaş 2020). The latest current approach of Alshaiba et al. (2020), (Fig. 12) uses mobile mapping system (MMS) to update basemaps. This system is proposed used when aerial photogrammetry cannot be applied.

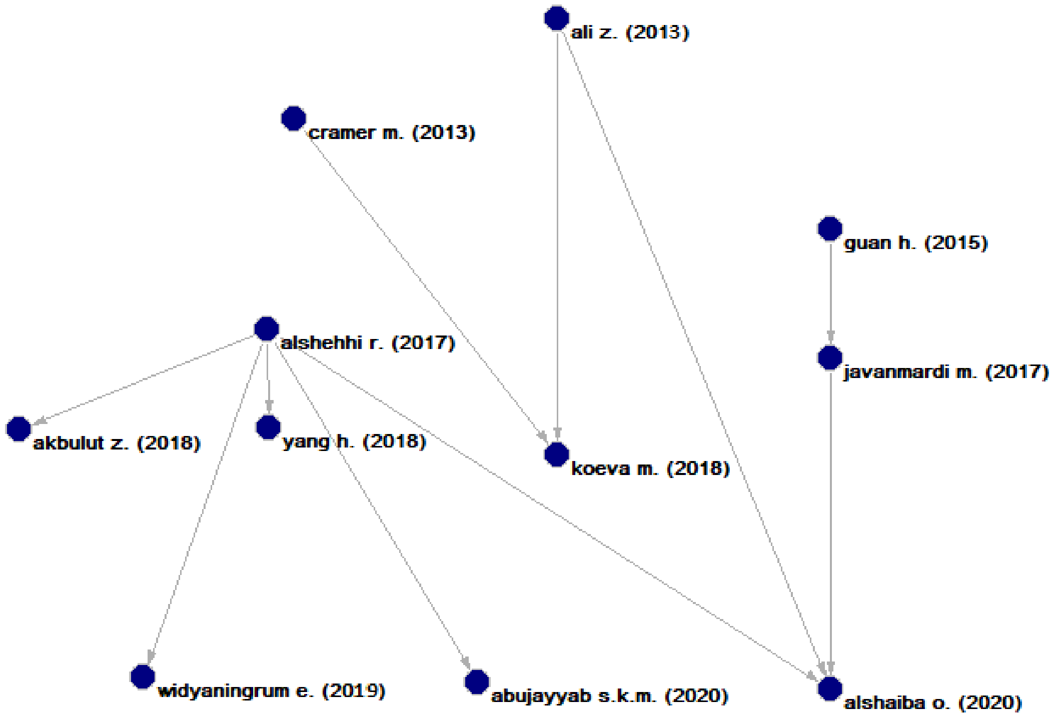

Fig. 12: Main path cluster 5

As a résumé within the overall research area updating digital building models is that there are four subordinate research streams derived from the four main paths described above: (1) Updating geo-databases based on aerial imagery and LiDAR data, (2) Updating BIM Models, (3) forest inventory updating through LiDAR and (4) updating cadastral maps via imagery and photogrammetry. The research activity for updating BIM models can be further divided into three subordinate streams: Updating schedule, updating construction site progress and updating the geometry of buildings (interior and exterior). The individual developments within the research areas were described. Although all research streams deal directly or indirectly with the updating of digital building models, the research stream (2) Updating BIM Models is the most important for the specific research question.

4.2.2 Keyword Cluster Analysis

As Shrivastava and Mahajan (2016) declare, analyzing keywords affords an opportunity for discerning the main research interests in any field. A network of keywords offers a comprehensive overview of a knowledge domain, providing an understanding of the existing research interests based on the most used keywords, and how they are intellectually connected and organized. In this study, the overview of the research area under investigation is extended by the keyword cluster analysis in addition to the CNA. The keywords co-occurrence network is produced using VOSviewer software version 1.615 of the Leiden University (cf. Fig. 13). The minimum number of a keyword occurrence was set at 10 to just show influencing keywords. Co-occurrence could simply be defined as the situation where two keywords occur at the same time. A typical co-occurrence network of keywords consists of nodes (representing the keywords) and edges (representing relations among sets of keywords). The exported CSV file from Scopus was used. Figure 13 shows the five clusters formed by the content of the keywords in distinct colours. The update approaches are divided into the clusters of digital planning and construction, radar in robotics and mapping, geoscience, remote data acquisition and GIS. The individual clusters are highly interconnected, but there are also links between the clusters (cf. Fig. 13). This shows that successful updating approaches from one research field have been transferred to other research disciplines.

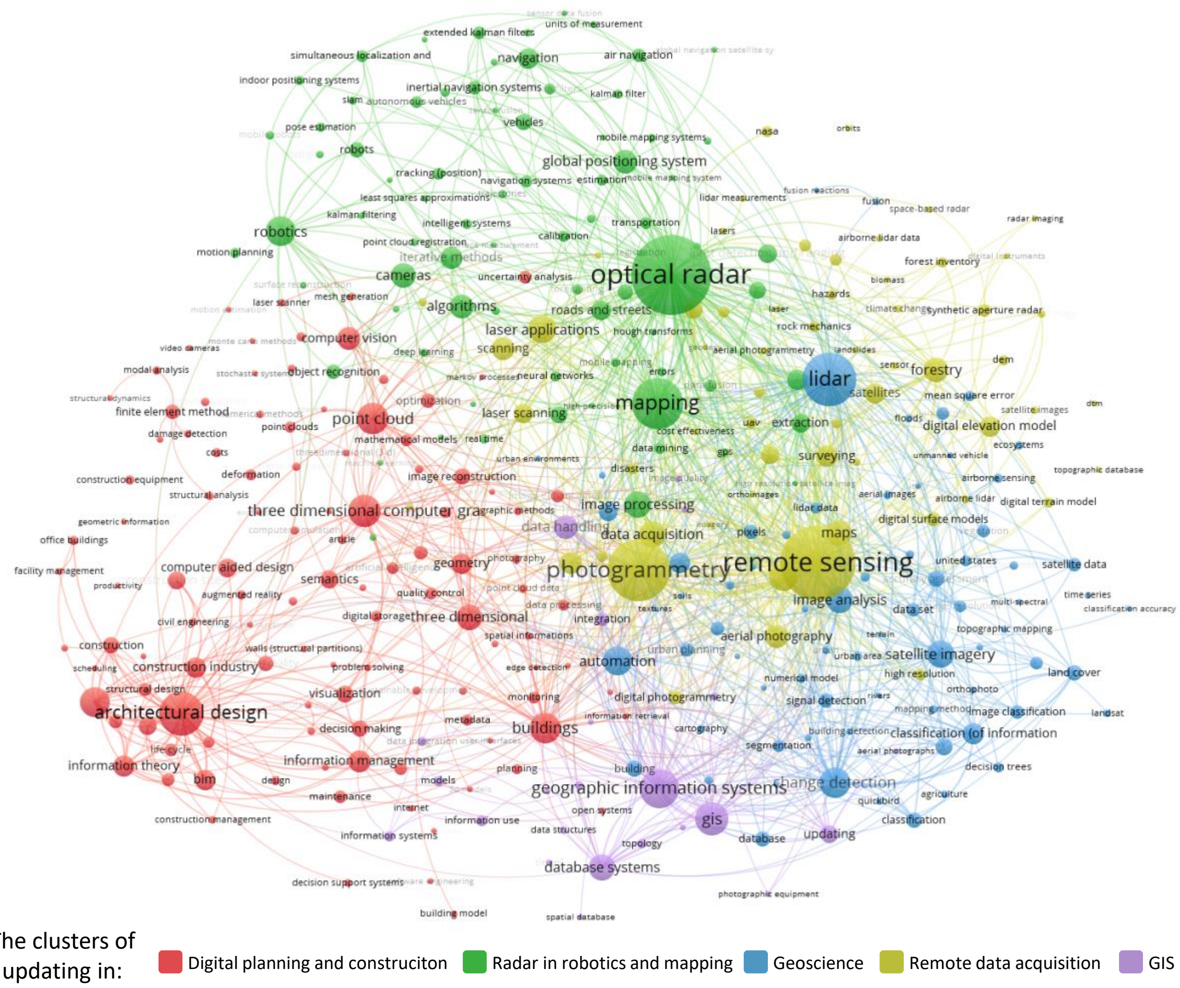

FIG. 13: Keyword co-occurrence network

Table 1 shows the 15 most frequently used keywords of each cluster with their frequency (number in brackets). Based on the keywords and their frequency the clusters were named. The following paragraphs comment on the content of the clusters through relevant articles and define the research areas within the literature about updating approaches. Literature from the first cluster for updating digital planning and construction data deals with the updating and merging of several data sources (Fig. 13). The approach of Lawrence et al. (2011) proposes a data coordination system that detects changes and transforms them into updates (Lawrence et al. 2011). The method is proposed for building design to convert design changes into cost updates. Another publication in this field of Yu et al. (2018) deals with the integration of BIM with other data sources such as IoT, scanning, VR and AR. Live updates of the various data sources are improving the productivity and efficiency. The intelligent site management model provides a basis for re-engineering the construction management process, helping to improve productivity and sustainability of the construction process. The need for up-to-date data was recognized and is based on the cooperation of all project participants, who keep the data model up-to-date.

Table 1: Distribution of keywords in the clusters

Digital planning and construction	Radar in robotics and mapping	Geoscience	Remote data acquisition	GIS
architectural design (156)	optical radar (357)	lidar (206)	remote sensing (328)	geographic information systems (133)
three dimensional computer graphics (102)	mapping (192)	change detection (95)	photogrammetry (251)	GIS (105)
point cloud (99)	robotics (89)	automation (88)	antennas (84)	database systems (77)
buildings (93)	image processing (75)	satellite imagery (81)	laser applications (84)	data handling (68)
building information model - bim (91)	cameras (69)	image analysis (75)	data acquisition (76)	updating (45)
three dimensional (74)	global positioning system (66)	classification (of information) (56)	maps (72)	integration (32)
computer vision (63)	algorithms (65)	image segmentation (54)	forestry (70)	information use (24)
information management (61)	iterative methods (59)	algorithm (47)	scanning (64)	information systems (20)
information theory (57)	feature extraction (55)	land use (41)	aerial photography (62)	models (20)
geometry (55)	navigation (53)	accuracy assessment (39)	surveys (59)	data integration (18)
bim (54)	roads and streets (52)	building (38)	surveying (56)	topology (18)
construction industry (53)	light detection and ranging (48)	database (36)	digital elevation model (53)	modeling (16)
computer aided design (49)	extraction (47)	classification (35)	satellites (53)	data structures (15)
project management (45)	object detection (42)	land cover (35)	laser scanning (52)	triangulation (15)
construction sites (44)	image matching (41)	pixels (34)	unmanned aerial vehicles (uav) (49)	image quality (13)

In the second cluster (radar in robotics and mapping) (Fig. 13 and Table 1), optical radar and LiDAR technologies are used to avoid labor-intensive and time-consuming updates of mapping systems. Furthermore, many update approaches are related to the research field of robotics. In a paper representative for this cluster Javanmardi et al. (2017) have presented a novel framework for automatic georeferencing of mobile mapping system (MMS) data that is specially designed for urban areas. Among others, the landmark update process was chosen as use case. An current publication on the subject of updates that is representative of the robotics sector is that of Buyval et al. (2018). The article presents an approach to fuse data from various sensors (camera, LIDAR, radar, intertial measurement unit) in the scope of the strongly researched topic of pedestrian and vehicle tracking. Publications from the field of geoscience (cf. Table 1) have already been presented in section 4.2.1 (Mainpath: Geoscience) and will not be discussed again. For the contents of the cluster "Remote data acquisition" (see Table 1), it is also referred to the main path analyses of LiDAR forest inventory update and Geoscience. Although the keyword cluster analysis distinguishes between the clusters Geoscience and GIS, these clusters are thematically very similar (cf. Table 1). Therefore, reference is made to section 4.2.1 (Mainpath: Geoscience) for the GIS cluster of Table 1.

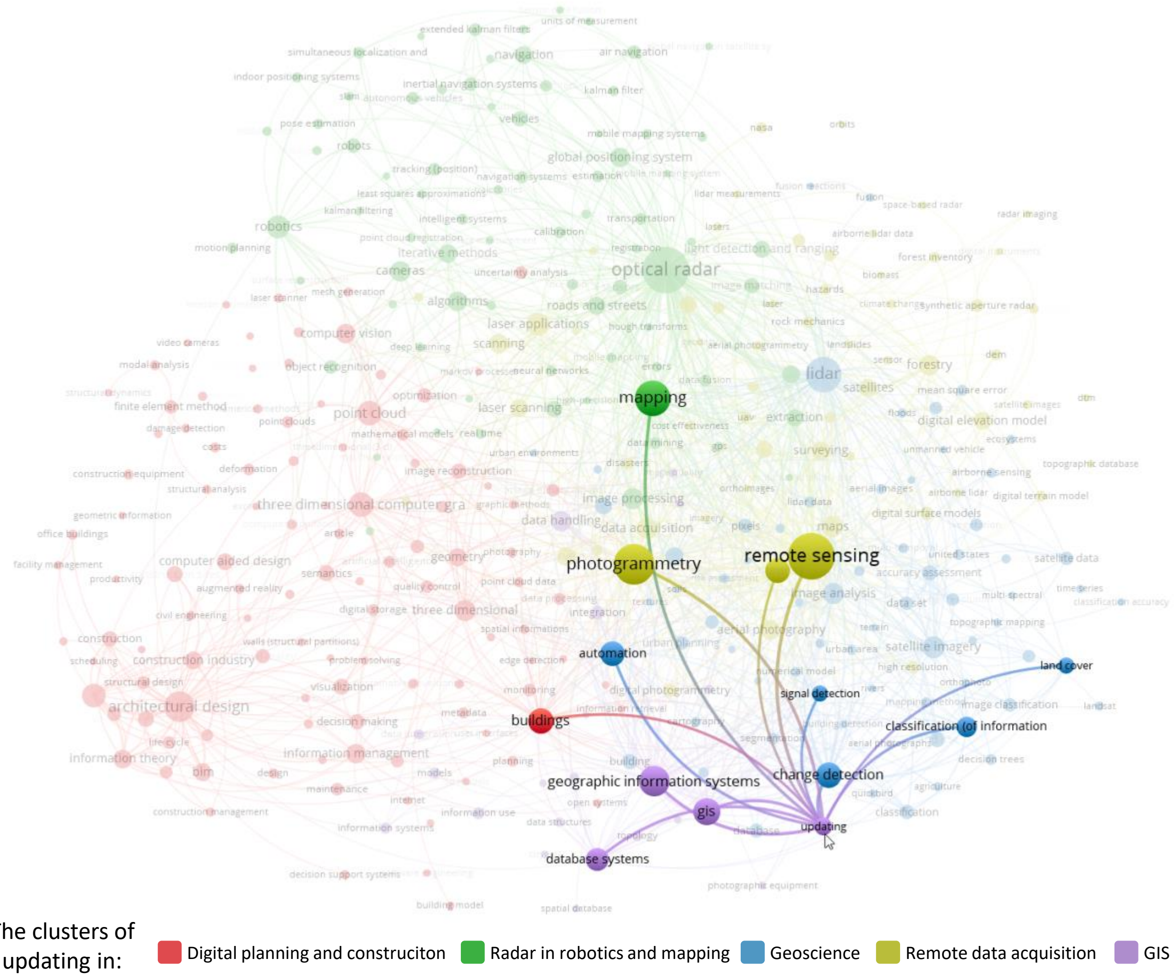

FIG. 14: Keyword co-occurrence network: Connections of updating

As shown in Figure 14, the updating (in the form of the keyword updating) affects all five clusters. The specific contents of the updating approaches within the clusters were presented to examine the updating issue from different perspectives. In this way, relevant approaches for updating digital building models can be identified. Updating approaches that have not previously been used directly for digital building models but have so far only been used in related research areas, can also be considered with this approach.

Analysing the chronological development of the different research streams, it can be clearly seen that photogrammetry and remote sensing approaches are among the most established update methods (cf. Fig. 15). As described in the previous sections, these can be counted among the research fields of geoscience and GIS. Around the year 2012 several update approaches for mapping, cadastral data and in this context for individual buildings have been developed (Fig. 15). After that, from 2013 onwards, the subject area of updating regarding the use of optical radar and LiDAR for robotics and driverless driving has been established. The update approaches for BIM and architectural design are shown in Figure 15 as the most recent research area. For updating building data during the planning or construction phase there are already some connections to suitable technologies such as LiDAR, photogrammetry or remote sensing (Fig. 15). For existing buildings, however, no literature and links to the updating approaches from the established research clusters can be identified, which indicates a research gap.

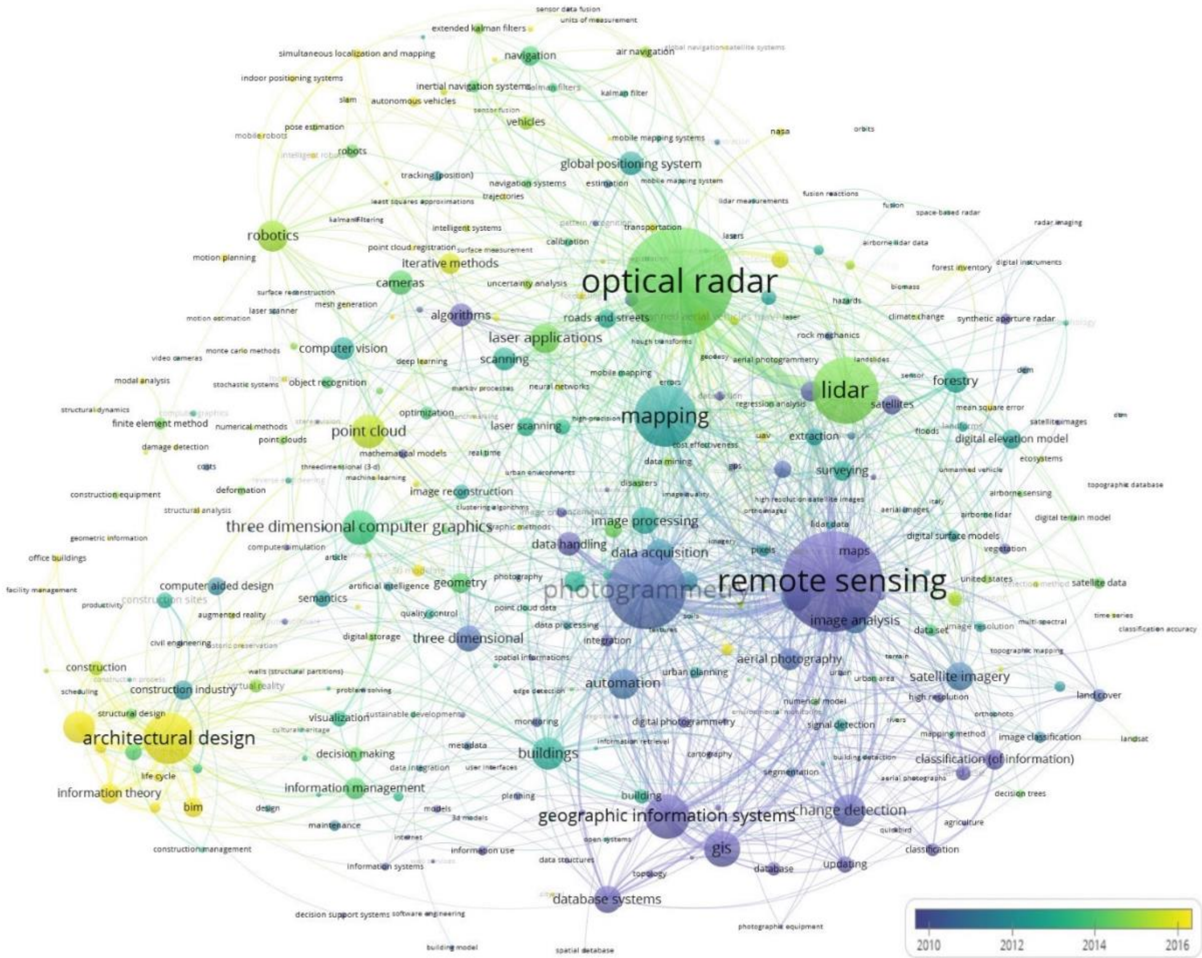

FIG. 15: Keyword co-occurrence network: Chronological development

4.2.3 Keywords burst detection analysis

The burst detection analysis provides insights into the popularity of keywords over time. The analysis contains information about both the duration and the weight of a trend within the topic. Its analysis can confirm or add further information to what has emerged in the previous analyses of the CNA and of the keywords co-occurrence network. In particular, the latest trends can suggest future research directions. Figure 16 depicts the temporal bar graph of Kleinberg's burst detection, which provides insights into the popularity of keywords dealing with updating of digital building models over time.

Compared with Figure 15, which shows the thematic development of entire research streams over time, Figure 16 depicts the temporal bar graph of Kleinberg's Burst detection with insights of specific keywords. The bursts characterized by the highest weight is 'GIS' and 'data', which can be linked to the keywords 'geographic information system' and 'database' (Fig. 16). The strong bursts from the year 2000 to approx. 2005 of 'GIS' and 'Data' are due to the numerous publications from the "Mainpath: Geoscience" section described above.

The many lower-weighted bursts from the year 2000 such as 'imag', 'remot' and 'autom' depicted by Figure 16, suggest the compound keyword imagery, remote sensing and automatic. These individual trends are reflected in publications such as that of Busch et al. (2004) in automated approaches for image processing and updating of topographic maps (Busch et al. 2004). The burst of photogrammetry runs from 2001 to 2009. An end to the trend of photogrammetry in 2009 can be explained by the still very long processing times (Kersten and Lindstaedt 2012). In addition to the fields of research, the bursts also show the specific methods used by the word beginnings such as ‘classif’ (2000-2004), ‘semant’ (2000-2003) and ‘kalman’ (2006-2007). This refers to the methods classification, semantic segmentation and Kalman filters. Some techniques such as image differencing of maps can only provide change/non-change information, while some techniques such as post-classification comparison can provide a complete matrix of change directions (Lu et al. 2004). An example for the use of semantic segementaton is training deep neural networks to perform semantic segmentation of point clouds of building interiors (Ma et al. 2020). The Kalman filter is used to fuse laser-scanned point clouds and tactile points to incrementally update surface models (Huang und Qian 2006). Current trends such as ‘point cloud’ (2013-2018), ‘scanning’ (2014-2015) and the use of UAVs (2016-2018) represent the latest developments in updating approaches (cf. Fig. 16). It is conspicuous that photogrammetric updating approaches are currently not represented in research despite significant improvements in processing times and the quality of the resulting models. In recent years (2013-2018), the focus of research has been put very strongly on laser scanning.

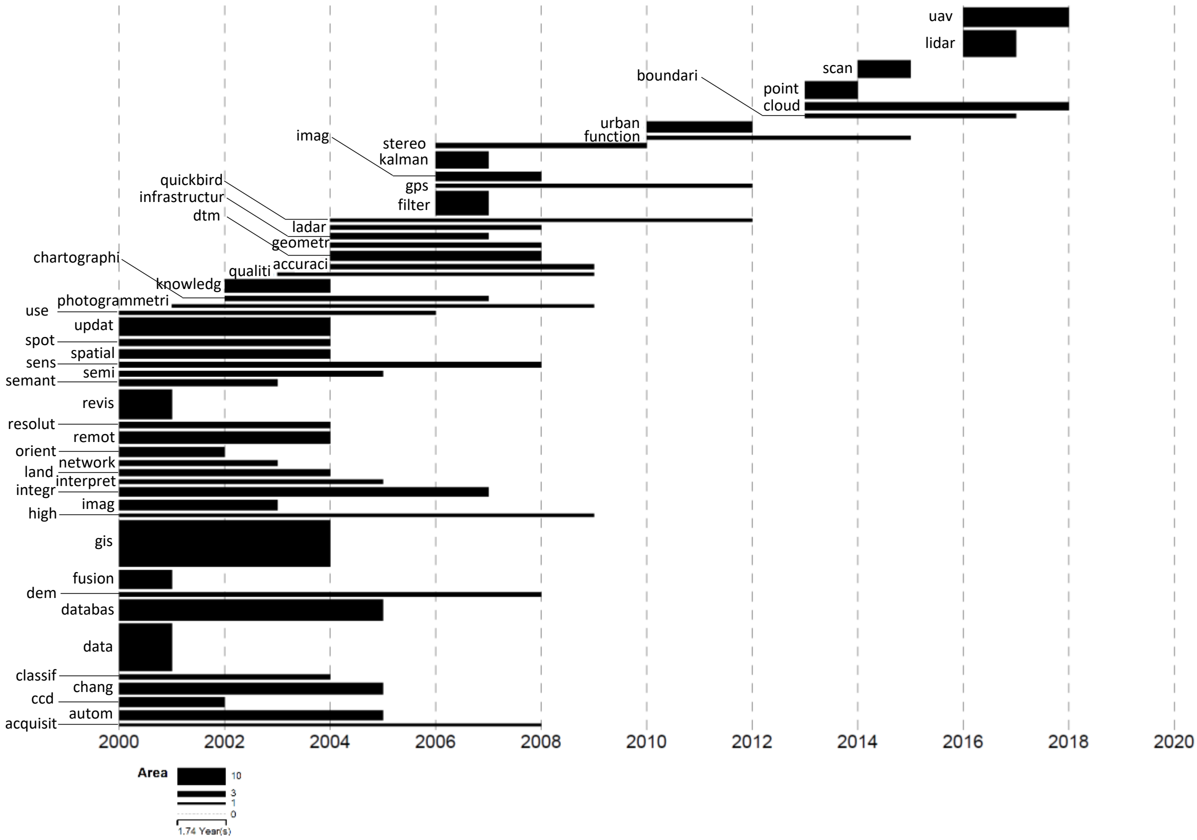

FIG. 16: Keywords burst temporal graph

4.2.4 Total citation score

The applied algorithm to detect the global key-route main path is based on the citation traversal weights (Liu und Lu 2012); this does not ensure that all the most cited papers are taken into account (Ciano et al. 2019) but only the ones that are important for understanding the development of updating approaches. Indeed, in this work among the fifteen most cited papers in updating approaches literature (Table 2), only eight papers belong to the main path.

The list was not only compiled according to the absolute number of citations. Also a check was carried out to determine whether the respective document was also relevant to the topic of digital building models. Thus, publications that are not part of the research focus were excluded. The list of documents with the highest citation score (Tab. 2) is intended to highlight the most influential publications in the research area with regard to updating approaches to digital building models. In the following, only those publications are presented which were not already discussed in the main path analysis.

Table 2: Fifteen most cited papers in updating approaches literature

Authors	Title	Year	Source Title	Citation count	Document type	Main path
Haala, N., Kada, M.	An update on automatic 3D building reconstruction	2010	ISPRS Journal of Photogrammetry and Remote Sensing	**286**	Journal Article	No
Whelan, T., Kaess, M., Johannsson, H., Fallon, M., Leonard, J.J., McDonald, J.	Real-time large-scale dense RGB-D SLAM with volumetric fusion	2015	International Journal of Robotics Research	**215**	Journal Article	No
Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., Park, K.	A formalism for utilization of sensor systems and integrated project models for active construction quality control	2006	Automation in Construction	**197**	Journal Article	No
Kim, C., Kim, C., Son, H.	Automated construction progress measurement using a 4D building information model and 3D data	2013	Automation in Construction	**139**	Journal Article	Yes
Bouziani, M., Goïta, K., He, D.-C.	Automatic change detection of buildings in urban environment from very high spatial resolution images using existing geodatabase and prior knowledge	2010	ISPRS Journal of Photogrammetry and Remote Sensing	**139**	Journal Article	Yes
Vastaranta, M., Wulder, M.A., White, J.C., Pekkarinen, A., Tuominen, S., Ginzler, C., Kankare, V., Holopainen, M., Hyyppä, J., Hyyppä, H.	Airborne laser scanning and digital stereo imagery measures of forest structure: Comparative results and implications to forest mapping and inventory update	2013	Canadian Journal of Remote Sensing	**125**	Journal Article	Yes
Klein, L., Li, N., Becerik-Gerber, B.	Imaged-based verification of as-built documentation of operational buildings	2012	Automation in Construction	**117**	Journal Article	Yes
Alshehhi, R., Marpu, P.R. , Woon, W.L., Mura, M.D.	Simultaneous extraction of roads and buildings in remote sensing imagery with convolutional neural networks	2017	ISPRS Journal of Photogrammetry and Remote Sensing	**115**	Journal Article	Yes
Thomson, C., Boehm, J.	Automatic Geometry Generation from Point Clouds for BIM	2015	Remote Sensing	**96**	Journal Article	No
Chen, X., Chen, J., Shi, Y., Yamaguchi, Y.	An automated approach for updating land cover maps based on integrated change detection and classification methods	2012	ISPRS Journal of Photogrammetry and Remote Sensing	**89**	Journal Article	No
Matikainen, L., Hyyppä, J., Ahokas, E., Markelin, L., Kaartinen, H.	Automatic detection of buildings and changes in buildings for updating of maps	2010	Remote Sensing	**81**	Journal Article	Yes
Han, K.K., Golparvar-Fard, M.	Potential of big visual data and building information modeling for construction performance analytics: An exploratory study	2017	Automation in Construction	**79**	Journal Article	Yes
Ham, Y., Golparvar-Fard, M.	Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling	2015	Automation in Construction	**76**	Journal Article	No
Kim, C., Kim, B., Kim, H.	4D CAD model updating using image processing-based construction progress monitoring	2013	Automation in Construction	**66**	Journal Article	Yes
Voegtle, T., Steinle, E.	Detection and recognition of changes in building geometry derived from multitemporal laserscanning data	2004	Archives of Photogrammetry and Remote Sensing	**61**	Joural Article	No

The most cited paper comes from Haala and Kada (2010) and deals with developments in the creation of 3D city models. The paper presents approaches to generate more detailed facade geometries from terrestrial data collection. The strong influence of the publication is based on active research in the field of automatic city modelling and updating. Whelan et al. (2015), (Tab. 2) presents a SLAM system that allows for efficient updating of dense maps (Whelan et al. 2015). The high number of 215 citations can be explained by the real-time capability of the system based on a cost-effective RGB-D sensor. The publication with the third most citations by Akinci et al. (2006) is dedicated to updating an as-planned model during the construction phase to an as-built model (Akinci et al. 2006). It also focuses on defect detection and management. The unique feature of the approach consists in the parallel use of different recording techniques. Thomson and Boehm (2015) published a highly visible paper dealing with an essential component of automated BIM updating: automated geometry generation from point clouds for BIM (Thomson und Boehm 2015). Such approaches can be summarised under the term Scan-to-BIM (Fig. 2) (Adán et al. 2020). Chen et al. (2012) publicised an approach for updating land cover maps based on remotely sensed data (Tab. 2) (Chen et al. 2012). The publication of Chen et al. (2012) has been cited 89 times so far (Tab. 2). The approach also incorporates change detection and classification methods. In the energy modelling of existing buildings, assumptions are often imprecise, as they do not take into account the reduction in thermal resistance caused by the deterioration of building materials. To improve the reliability of BIM-based energy modelling, Han and Golparvar-Fard (2017) present a system for automated mapping and updating of actual measurements of thermal properties with BIM elements in the gbXML schema. Though this approach considers a very special update topic from the field of building physics, it achieves a remarkable response with 76 citations. The publication of Voegtle and Steinle (2004) deals with the detection of changes in urban areas after strong earthquakes (Voegtle und Steinle 2004). The detection and classification of these changes is based on airborne scanning images. The approach can therefore be attributed to geoscience.

4.3 Systematic literature review (steps 5-7)

Following the bibliometric analyses, the SLR steps will be continued by adding relevant publications not listed in Scopus in order to get a comprehensive overview of existing update approaches (Fig. 4). Finally, the results are summarized.

In order not to be limited exclusively to the literature database Scopus, publications from other literature databases like Web of Science or open platforms like Google Scholar were also identified. Five further publications relevant to the topic can be added to the existing stock: The first added publication is a dissertation by Macher (2017) which addresses the scan-to-BIM topic and presents a semi-automated approach for existing buildings (Macher 2017). The approach can be seen as a preliminary stage of the upgrade, as it captures the as-built geometry of the building by processing interior scans. The second publication is from Fuller (2009) and presents a software architecture for self-updating BIM models (Fuller 2009). The approach is based on the integration of sensors to make the static BIM model active as well as dynamic. The third added publication is a dissertation by Tuttas from 2017, which proposes an approach to construction progress control based on photogrammetry (Tuttas 2017). The aim is to update the as-planned BIM using the as-built information. A multi-view-stereo method is used to generate dense photogrammetric point clouds. The fourth publication added was published by O'Keeffe and Bosché (2015) and highlights the importance of open source and the combination of BIM and photogrammetry (O'Keeffe und Bosché 2015). A web-based, real-time and bi-directional interface between BIM models and 3D photo data is developed. The fifth publication added is a master thesis by Conrads (2018) which analyses the geometric accuracy of 3D building models using LiDAR data (Conrads 2018).

5. RESULTS

From the mainpath analysis, keyword co-occurence network analysis and the derived clusters, it was possible to identify fields of research that provide approaches for updating with different focuses. The individual research areas that directly or indirectly deal with the updating of digital building models based on the literature analysis are shown in Figure 17. The literature sources assigned with the research areas in square brackets in Figs. 17 and 18 are itemized in Table 4. All fields of research, except built heritage modeling, have already been dealt with in the previous sections. The research field of built heritage modeling was only partially covered by the search term used and is therefore underrepresented, although this research field also contains interesting approaches for updating digital building models. An overview of Heritage BIM (HBIM) is provided by the publication of Yang et al. (2020), which presents the current state of approaches for modeling the geometry, information management and ontology tools of heritage.

With regard to the research question, the publication by Russo et al. (2019) seems particularly interesting in the field of HBIM and cultural heritage (Russo et al. 2019). Here smartphone cameras are tested to what extent they can be used for photogrammetry applications by architects and restorers. It becomes clear that with increasing distance (approx. 12 m) from the recorded object, the inaccuracies increase in comparison to the results of the laser scanner. However, the goal of the publication is the initial recording of the actual state, not a continuous updating of the geometry. However, this paper shows that the use of photogrammetry applications with smartphones in the research field of HBIM to update changes that occur is theoretically possible.

The fields of research identified in the SLR and BLR are shown with representative literature in Figure 17. The mainly applied techniques of the research fields and the derived information therefrom are listed in Table 3. It is evident that geometric surveying techniques predominate. Pure semantic surveying is not observed in any research field.

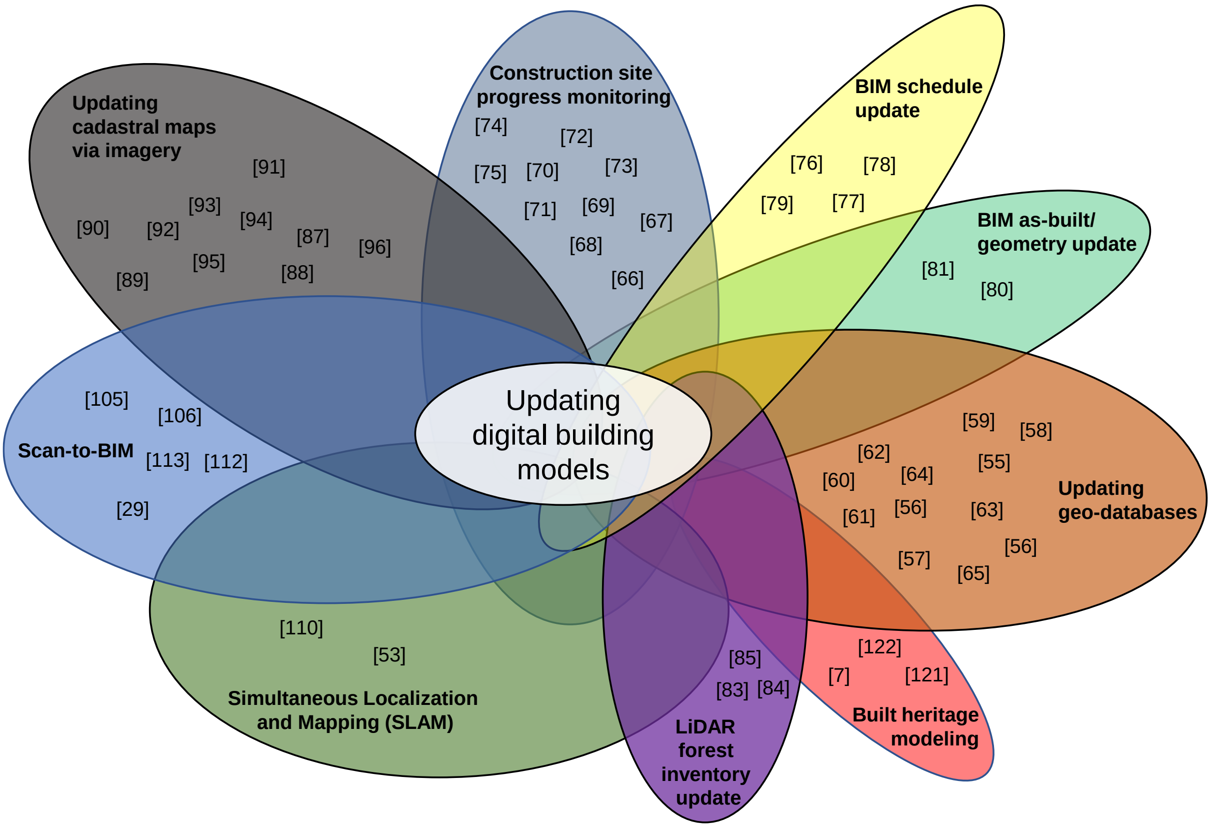

FIG. 17: Updating approaches and their intersection with the updating of digital building models (geometry and semantic information) (References according to Table 4)

Table 3: In the fields of research applied techniques and derived information

Fields of research	Applied technique	Derived information
Scan-to-BIM	Laser scanning, BIM-Modeling	Geometric and semantic information
Updating cadastral maps	Photogrammetry, Videogrammetry	Geometric information
Construction site progress monitoring	Laser scanning, Photogrammetry	Geometric information
BIM schdule update	Photogrammetry, Laser scanning, Analysis of preexisting information	Geometric and semantic information
BIM as-built/ geometry update	Laser scanning, Contact methods, Photogrammetry	Geometric information
Updating geo-databases	Photogrammetry	Geometric information
Built heritage modeling	Photogrammetry	Geometric information
LiDAR forest inventory update	Laser scanning	Geometric information
SLAM	IoT	Geometric information

The nine identified research fields in Figure 17 often differ only in their field of application. The imaging and scanning technologies used are mostly identical (Table 3). This results in an increased potential for transferring an approach from one research field to another research field. Among the identified research areas there are also very similar research areas such as 'Scan-to-BIM' and 'BIM as-built/ geometry update', which differ only in their objectives (Fig. 17). Scan-to-BIM focuses on the automated creation of detailed semantic as-is 3D models based on point clouds created by scanning techniques. This is a very broad and active field of research. The research field "BIM as-built/ geometry update" shown in Figure 17 focuses more on cost-effective methods to verify and update the as-is state of a building. Image-based methods are less used compared to scanning methods. Thus, the aspect of updating existing buildings with imaging technologies has been poorly represented in the literature until now. The strong representation of updating approaches in the research areas 'Updating cadastral maps via imagery' and 'Updating geo-databases' is connected with the efforts of state administrations to have current cadastral and building data available in their regions. In Germany, for example, a nationwide and uniform 3D building stock is modeled on the basis of a technical schema for 3D building models (AdV-CityGML-Profile) (Aringer et al. 2016). After the broad examination of updating approaches in different spatial research areas (cf. Fig. 18), the focus is placed on the individual building with its manifold dimensions (cf. Fig. 18). For individual buildings the identified approaches can be divided into three different perspectives: Surveying technique perspective, building phase perspective and spatial perspective (cf. Fig 18).

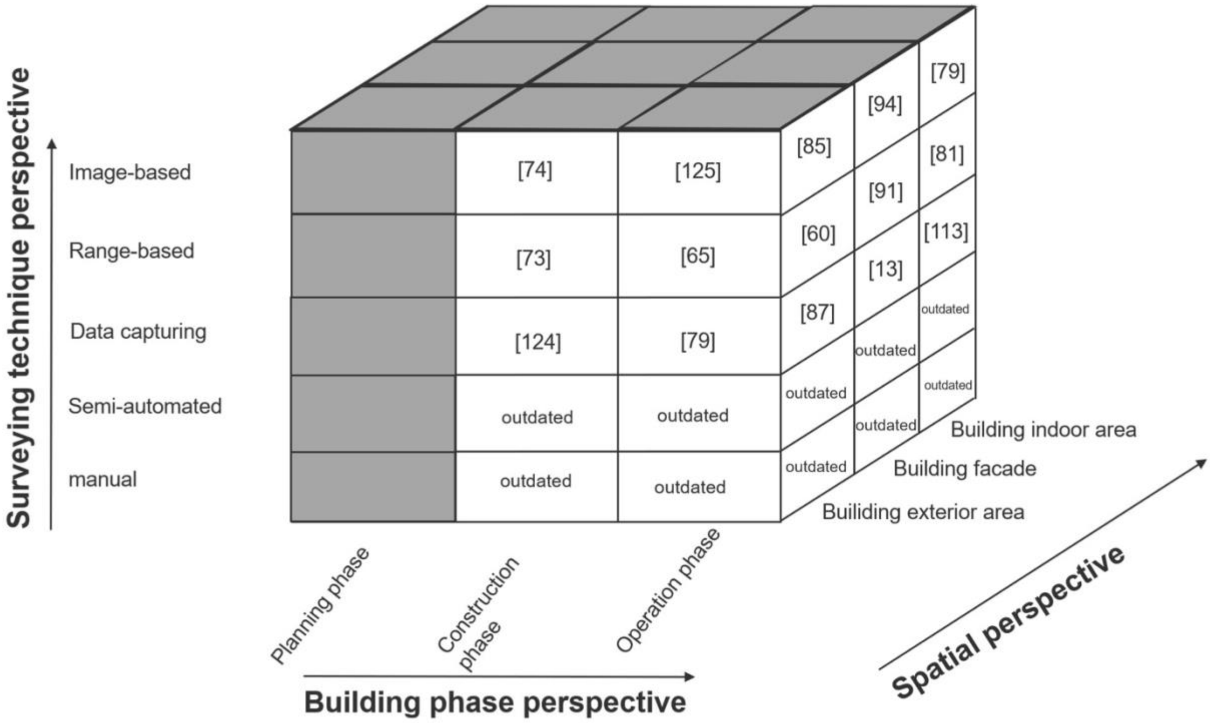

FIG. 18: The three updating approach perspectives and their representatives in building context (References according to Table 4)

Considering the phases shown in Figure 3, the building life cycle can be divided into the phases planning, construction and operation. The identified approaches with regard to the spatial perspective can be attributed to the building exterior area, the building facade or the building indoor area. Regarding the technologies applied (Fig. 1), approaches in literature can be divided into image-based, range-based, data capturing, manual and semi-automated techniques. Considering these distinguishing features the approaches can be summarized in three perspectives (cf. Fig 18). The three perspectives (surveying techniques, building phases and spatial) make it possible to correlate literature sources of the different perspectives or categories. Grey areas are irrelevant for update approaches or do not belong to any identified perspective. The planning phase is not considered except for an approach aiming at BCF-based (BIM collaboration format) updating of planning content. Approaches of the manual and semi-automated techniques are not considered because they no longer represent the state of the art from the year 2000 onwards. The publication named in the fields is representative for the composition of the two considered perspectives. For example in the surveying technique perspective data capturing in the construction phase is represented by (Louis und Dunston 2018). In all of the updating fields identified (Fig. 18) (except for image-based/operation phase), reference can be made to a large number of literature sources. It is noticeable that the only approach for updating digital building models via photogrammetry (image-based) of existing buildings in the operation phase is the one of Hellmuth et al. (2020). Another approach considering image-based updating during the operational phase is the publication by Klein et al. (2012). Here the update is mentioned several times, but the actual focus is on a verification of the as-built situation. The update approaches shown in Figures 17 and 18 provide the overview of existing update approaches from the literature sought in the research question. Taking into account all distinguishing perspectives and features, there are also numerous approaches that combine several categories or recording techniques. In Figure 18, however, only publications that combine two perspectives are ever mentioned representatively. Approaches that combine, for example, image-based and range-based recording techniques (Aringer et al. 2013) are not considered in Figure 18, but do exist. The previously mentioned publications in the field of HBIM can be assigned to the Building phase operation (Fig. 18).

Table 4: Assignment of literature sources in Figure 17 and 18

[1]	van Berlo and Krijnen, 2014	[66]	Kim, Son, Kim, 2013	[87]	Ali et al., 2013
[7]	Galantucci and Fatiguso, 2019	[67]	Wang and Cho, 2015	[88]	Cramer et al., 2013
[9]	Brilakis et al., 2011	[68]	Han and Golparvar-Fard, 2016	[89]	Guan et al., 2015
[12]	Donath, 2009	[69]	Mandava et al., 2018	[90]	Alshehhi, 2017
[13]	Hui, 2018	[70]	Kim et al., 2018	[91]	Akbulut et al., 2018
[18]	Burak Gunay et al., 2019	[71]	Zhang and Huang, 2019	[92]	Yang et al., 2018
[29]	Czerniawski and Leite, 2020	[72]	Pour Rahimian et al., 2019	[93]	Koeva et al., 2016
[31]	Lu et al., 2020	[73]	Gao et al., 2015	[94]	Widyaningrum and Lindenbergh, 2019
[53]	Andert et al., 2017	[74]	Amer and Golparvar-Fard, 2018	[95]	Abujayyab and Karaş, 2020
[55]	Zhang, 2004	[75]	Lin et al., 2019	[105]	Ma et al., 2020
[56]	Holland et al., 2006	[76]	Kim and Son, 2013	[106]	Huang and Qian, 2006
[57]	Bouziani et al., 2010	[77]	Kim, Kim, Kim, 2013	[110]	Whelan et al., 2015
[58]	Matikainen et al., 2010	[78]	Tserng et al., 2014	[112]	Thomson and Boehm, 2015
[59]	Pang et al. 2004	[79]	Hamledari et al., 2018	[113]	Adán et al., 2020
[60]	Qin and Gruen, 2014	[80]	Klein et al., 2012	[121]	Yang et al., 2020
[61]	Awrangjeb et al., 2015	[81]	Sepasgozar et al., 2014	[124]	Louis and Dunston, 2018
[62]	Awrangjeb, 2015	[82]	Wulder and Seemann, 2003	[125]	Hellmuth et al., 2020
[63]	Du et al., 2016	[83]	Wulder et al., 2008		
[64]	Cao et al., 2020	[84]	Hilker et al., 2008		
[65]	Zhou et al., 2020	[85]	Ali-Sisto and Packalen, 2017		

6. CONCLUSIONS

By combining SLR and BLR, a step-by-step approach to the research question posed could be achieved.

The bibliometric literature review initially showed an increasing research interest in updating approaches of digital 3D building information with the presentation of publications per year (cf. Fig. 6). The analysis of the citation network (cf. Figs. 7 and 8) first roughly identified the individual research streams. Subsequently, the main path analysis allowed to trace the contents and the development of knowledge of the individual research streams: Geoscience, BIM, LiDAR forest inventory update, Updating cadastral maps via imagery and photogrammetry. The subsequent keyword cluster analysis presented the most frequently used keywords in this research area and showed their connections to each other (cf. Fig. 13): Optical radar, remote sensing, photogrammetry, LiDAR, mapping and architectural design are the most used keywords of the research string (Fig. 13 and Tab. 1). The clusters associated with the keywords have also provided information about research areas that are involved in updating spatial data (cf. Table 1). This shows, for example, that laser scanning and photogrammetry are the most commonly used technologies to update 3D building information. The chronological development of the publications with the associated keywords has also shown that update approaches for architectural design are much younger than those from geoscience (cf. Fig. 15). The burst detection shown in Figure 16 also pointed out trends and research foci in the individual years. The distribution of photogrammetric, LiDAR and scanning approaches could be detected. Finally, influential authors and their publications were presented in a list (Table 2), whereby the most important and influential update approaches were identified.

By evaluating the analyses it could be determined that with regard to the building life cycle phases, the operation phase offers the least attention in the literature and thus very few approaches for updating digital building models of existing buildings. This finding is very surprising, since in production-related buildings such as factories exists an enormous need for up-to-date data (Kurniadi et al. 2018) and, thus, also up-to-date building models (Bartels 2020; Terkaj et al. 2015). In factory planning, up-to-date digital building models are required in order to support conversion processes at short notice (Terkaj et al. 2015; Melcher et al. 2018; Volk et al. 2014; Buede und Miller 2016). As many publications have recognised the need for the availability of up-to-date digital building models, it is assumed that updating approaches will become more important in industries such as factory planning, which is increasingly active in the brownfield (Schindler und Verl 2018) and, hence, relies on up-to-date digital building models. In the past, photogrammetry was used less frequently for updating building structures than laser scanning because of the long post-processing times and the often still too poor resolution of photographic devices. It is expected that the rapid development of photographic devices, especially smartphones, will result in photogrammetric applications being used more frequently in the future. In this paper only the most important and largest research areas involved have been considered. A more detailed examination would be possible, but would go beyond the scope of this paper. Based on the study, it was recognised that updating approaches for digital building models during the operational phase are necessary, but do not yet exist. Thus, future research activities should deal with the development of updating systematics that are based on photogrammetry and capture small-scale changes during the operational phase of buildings or factories.

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