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Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis

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ABSTRACT

Building Information Modeling (BIM) has emerged as one of the key streams in construction and civil engineering research within the last decade. Given this interest in BIM and the rapidly increasing volume of BIM literature, it is important to understand and discern the core themes and trends emerging in BIM research, and its implications for broader research. The previously reported studies to identify the core of BIM research are typically subjective and qualitative, and hence, prone to bias and interpretation of a limited number of reviewed papers. There is a lack of comprehensive, quantified and systematic classification of the BIM literature. This research brings some clarity by synthesizing and labeling a large corpus of BIM research studies published from 2004 through 2014. Latent Semantic Analysis (LSA), a natural language processing technique was applied to the abstracts of 975 academic papers. This objective analysis reveals twelve principal research areas. Various specific research themes associated with each principal area have been identified. These principal research areas and research themes indicate the patterns and trends in BIM research.

1. Introduction

Building Information Modeling (BIM) has emerged as one of the key streams in construction and civil engineering and received a considerable amount of attention by researchers within the last decade, with a rapid increase in the number of related publications. The rapid increase in the volume of BIM literature poses a critical challenge in terms of identifying the research direction and trends, because despite the increasing volume of the literature, the core of BIM research and related themes remain unclear and poorly understood. Previous efforts to review the trends in academic BIM literature are typically qualitative, subjective and based on manual review. These reviews such as [1–6], provide an elaborate guidance, categorization and framework for implementation, adoption and technologies of BIM to the various participants of a project and to the researchers. Others such as [7–11] have discussed trends and future directions based on surveys, critical literature reviews, often with a specific frame of reference such as BIM for facilities management or so on.

The manual review, while insightful, is prone to be biased and limiting in terms of the number of articles that can be reviewed. In such manual reviews there is a potential tendency to read the more cited and influential papers, which while being a valid approach for review, might not be a comprehensive representation of the patterns in BIM literature. That is, it is important to note at the outset that we distinguish between critical review and patterns in literature. Instead of conducting a qualitative and subjective evaluation as to which themes are more important, we are interested in quantitative assessment based on textual analysis on how often the different themes have emerged in the BIM literature. The frequency and occurrence of themes can be assessed through semantic grouping of the keywords using techniques such as Latent Semantic Analysis (LSA), and such methods are well established as valid and useful methods to understand the patterns in literature.

LSA, as a text data mining and natural language processing (NLP) technique allows a systematic, computational and comprehensive analysis of a large corpus of literature for matching between query and document at topic level. In addition to the application areas of text data mining and NLP techniques across various disciplines, recent studies also demonstrate the viability of these techniques for the architecture, engineering and construction (AEC) industry. Similar text-based data mining and NLP techniques have been shown to be useful in the AEC industry for various aspects such as information retrieval, increasing the efficiency in decision making, predicting cost over-runs, reducing the human efforts, reducing errors in recognitions, and dispute resolution in construction accidents [12–21].

This research brings a structured representation of the patterns in BIM research by systematically applying LSA techniques to a large corpus of academic BIM articles published from 2004 through 2014. This systematic analysis of 975 paper abstracts reveals twelve principal BIM research areas. In addition, ninety specific research themes associated with the twelve principal areas have been identified and clustered.

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These principal research areas and research themes comprise the comprehensive patterns of BIM research, which indicate the directions and trends in BIM research. The outcomes of analysis presented in this paper also provide opportunities for the researchers/professional to position their future BIM research and/or implementation strategies.

The paper is organized into three main sections. The first section describes the research data and the research methodology. This includes a detailed description of the data collection process, the LSA technique and its application to the collected data. The second section describes the results and findings from the analysis. Results are presented at various levels of details, ranging from twelve key principal research areas to ninety specific research themes. A cross analysis across the twelve principal research areas and ninety specific research themes is presented to identify their links. The third and final section concludes the paper with a brief discussion on the usefulness of the research findings, the limitations of the reported research, and the implications for future research.

2. Methodology and research data

The research data comprised of academic journals and conference papers collected through multiple academic databases and sources. Conference papers are in general less rigorously reviewed compared to the journal articles. However, they are included in the corpus, because instead of comparing or evaluating the strength or quality of studies, this paper aims to reflect the interest of research community on BIM topic. The following definition of BIM by the National Institute of Building Sciences buildingSMART alliance is considered as a fundamental reference to choose the relevant papers.

> "*A BIM is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward*"
>
> [22]

There are three steps applied to collect and finalize the data. Initially the articles were identified using the search phrase "building information modeling" in their titles and/or abstracts and/or keywords. Instead of using "bim" by itself, which also represents other research topics from disciplines such as genetics or economics, phrases "bim" AND "building" and "bim" AND "information modeling" were used together to enlarge the corpus size. BIM-related textbooks, trade magazines, brochures and product/software related white papers were not considered, because the analysis focused on research publications. Since most research reports and theses result in academic articles, they were also not considered to prevent duplication in the corpus. Initially 980 paper abstracts were collected in the corpus. In the second step, "building information modeling" AND "bim" search phrases together in "full text" of the documents. In this step, the queried papers were manually screened to decide whether it is relevant to include in the corpus. If the searched keyword exists in an example, citation or acknowledgement, the related paper was not added to the corpus. At the end of this step, 89 more abstracts were added to the corpus. Table 1 summarizes the document collection process.

Table 1
Criteria for paper search and collection.

Round #	Search criteria	Number of papers collected
1	Search phrases/Within databases/ In Title OR Abstract OR Keywords	980
2	Search phrases/Within databases/ In full text	89
3	Elimination of duplications	94
Total		975

The 1069 abstracts (documents) collected through different sources were reviewed to eliminate duplication in the final step. After the final processing, 975 documents were saved in the research corpus. Tables 2 and 3 summarize the top sources of the included documents. Table 2 shows the distribution across the databases with the number of journals (J) and conferences (C), and Table 3 lists the top 20 contributing journals (J), showing the distribution of papers by year.

3. Data analysis

3.1. Introduction to Latent Semantic Analysis

The BIM literature dataset (corpus) is subjected to Latent Semantic Analysis (LSA), a data/text mining technique used to facilitate retrieving and querying large corpus of data [23–25]. As a mathematical and statistical method, LSA is used to identify the latent concepts within the textual data at the semantic level [26]. LSA employs a set of algorithms to convert unstructured text into structured data objects, and analyze these data objects to identify patterns for the discovery of knowledge [27]. The main idea behind LSA is to collect all the contexts belonging to the words in the corpus, and derive associated factors that represent related concepts. In this paper, a factor can be defined as a latent class representing multiple observed entities which have similar patterns that associated with the latent class. For example, in a 12 factor analysis, all the relevant entities that were found in the corpus relevant to the analysis are classified or represented through 12 latent classes, such that each of the entities in corpus is associated with or shows similar patterns to one of the 12 latent classes. Thus, each factor reserves and represents a certain amount of the overall observed entities, and the factors are organized in the order of how many entities they explain. A sample representation of factors and their associated entities are presented in Table A1 for information science discipline in [25]. A similar example is also presented in Table 4 for a five-factor solution to articulate the relationship between factors and corresponding high-loading terms. In any text, multiple words may share the same meaning and one word may have many synonyms in different contexts. LSA "loads" the words that share the same meaning to their associated concept and also "loads" one word to various latent semantics other than its main associated concept.

LSA differs from traditional factor analysis by applying Singular Value Decomposition (SVD) to reduce the dimension of the original data. This helps to present the collected 975 papers under the categories aggregated variously. Using SVD, LSA generates two sets of loadings in matrix format, one for the terms and one for the documents. Each factor in the matrices is associated with a high-loading term or a high-loading document, where each factor represents a research theme in the corpus. Higher term/document loading values for each factor indicate a greater possibility that the related term/document discloses certain theme. The researcher can alter the level of detail for identifying the research

Table 2
Number of papers collected across different databases.

Database Name / Years	2014–12		2011–09		2008–06		2005–04		TOTAL	
	J.	C.	J.	C.	J.	C.	J.	C.	J.	C.
ASCE	63	53	15	30	4	22	0	2	82	107
CuminCAD	4	47	2	39	4	30	0	35	10	151
CIB-Library	0	9	0	50	0	9	0	2	0	70
EBSCO	2	0	7	0	2	0	0	0	11	0
ELSEVIER-Science Direct	153	0	58	0	21	0	7	0	239	0
EMERALD	15	0	7	0	5	0	2	0	29	0
IEEE Xplore	0	39	0	31	0	12	0	0	0	82
Proquest	54	22	8	10	7	3	1	2	70	37
SpringerLink	9	0	5	0	0	0	2	0	16	0
Taylor & Francis	35	0	11	0	2	1	1	1	49	2
Wiley Online Library	9	0	2	0	7	0	1	1	19	1
TOTAL	344	170	115	160	52	78	14	43	525	450

Table 3
Number of journal articles from different journals (only the top 20 are listed here).

Journal name/year	2014–12	2011–09	2008–06	2005–04	Total
Automation in Construction	75	42	8	0	125
Advanced Engineering Informatics	25	17	3	1	46
Journal of Computing in Civil Engineering	24	5	0	0	29
International Journal of 3-D Information Modeling	24	0	0	0	24
Journal of Construction Engineering and Management	12	7	0	0	19
Architectural Design	4	8	0	0	12
Construction Innovation: Information, Process, Management	6	4	2	0	12
Journal of Professional Issues in Engineering Education and Practice	9	3	0	0	12
Architectural Engineering and Design Management	4	6	1	0	11
International Journal of Architectural Computing	4	6	1	0	11
Shigong Jishu/Construction Technology	10	1	0	0	11
Practice Periodical on Structural Design and Construction	9	0	0	0	9
Procedia Engineering	5	4	0	0	9
Building and Environment	4	3	0	0	7
Civil Engineering	3	4	0	0	7
Computer-Aided Civil and Infrastructure Engineering	4	2	1	0	7
International Journal of Construction Education and Research	6	1	0	0	7
Computer-Aided Design	3	2	1	0	6
Energy and Buildings	6	0	0	0	6
Journal of Civil Engineering and Management	6	0	0	0	6
Other selected journals	102	39	8	0	149
Total	345	154	25	1	525

themes by changing the number of factors in the analysis. Lower level factor aggregation represents common research areas, and higher level factor aggregation represents principal research themes [25].

The steps in applying LSA to the BIM corpus is similar to previously reported studies [24,25,28]. These steps include the following.

3.2. Applying text-mining process including tokenization, stemming, stop word filtering, N-grams in a text-mining software

The following series of text-mining procedures is applied to the corpus within Rapidminer 5.0, a predictive analysis and data mining software: 1) Abstracts are tokenized with non-letter separators such that each abstract is aggregated to singular words that make the abstract an individual word-bag; 2) all the letters in the word bags are transformed to lowercase; 3) stop words of English such as "and", "the", and "so", are pre-defined in Rapidminer 5.0 (In addition, the keywords ("building", "information", "model", "building information", "information modeling", "building information modeling" and "bim") which were used during document collection; and such complementary words are custom defined to remove from the word-bags.); 4) the tokens of the words that are less than two letters are removed, because these tokens are grammatical necessity but do not add any meaning to the words; 5) term stemming techniques are applied to the word-bags, whereby the variations of the words are removed, evaluated with their grammatical roots and considered as a token (For example the words "communicate", "communication", "communicative" are transformed to a single token "communica-".) and 6) the last step of text mining is applying n-gram model. N-gram is a contiguous sequence of text or speech, which creates word groups that are considered as an individual token in the word-bag. For example the phrase "building information modeling" is aggregated to tokens "build-", "inform-", and "model-". With n-grams, the tokens "build_inform" and/or "build_inform_model" can be created. In this analysis, initially three-worded (trigram), and then two-worded (bigram) N-gram analysis was performed.

3.3. Output of text mining processes: term occurrences (TO) and term reduction

Initially the dataset was analyzed with trigram tokens and 153,306 entities were derived. However, during the dimensionality reduction, 87% of the entities were removed from the matrix due to their existence in one document or only one time, including most of the three-word entities because these documents do not give any meaningful contribution to the entire corpus. Therefore, the trigram analysis was discarded, and instead a bigram analysis was used. With bigrams, 64,812 entities were derived out of 975 abstracts. Term occurrences were sorted in descending order. The 49,460 entities that appeared one time, and the 50,972 entities that appeared in only one of the abstracts, were removed from the matrix to reduce the dimension. Although many two-word entities appeared in the removed entities, many of them were still left behind in the remaining matrix. Thus, the bigram analysis was acceptable. After the removal process, a $13{,}840 \times 975$ matrix was generated, which was still too large a matrix to perform an effective analysis. Therefore, following the steps in [29], the entities that appeared less than five times in the whole corpus were removed from the matrix. After this step a 3435×975 initial term-by-document (t–d) matrix was generated.

Table 4
Five-factor solution results and associated high-loading tokens.

F5.1	Implementation and adoption	construct, project, industri, technolog, design, manag, engin, process, adopt, collabor, architectur, integr, practic, paper, construct_industri, student, implement, educ, use, research, bim_technolog, model_bim, develop, applic, team
F5.2	Energy management	energi, design, perform, simul, system, build_energi, energi_perform, energi_consumpt, consumpt, effici. energi_effici, sustain, tool, base, sensor, studi, use, arrang, analysi, data, develop, build_design, energi_simul, assess, research
F5.3	Design practices	design, architectur, digit, space, process, parametr, architectur_design, design_process, tool, urban, system, code, interact, paper, represent, use, structur, comput, method, spatial, user, student, base, develop, build_design
F5.4	Information standards	ifc, data, standard, base, system, exchang, interoper, semant, structur, develop, use, object, softwar, applic, paper, industri, spatial, manag, space, method, approach, propos, foundat_class, requir, product
F5.5	Safety management	construct, safeti, system, project, plan, manag, schedul, site, accid, base, use, visual, hazard, case, check, risk, develop, activ, work, studi, process, construct_project, result, autom, time

As a last step in term reduction, an initial SVD was applied to the initial t–d matrix [25]. Communality values were calculated to identify the variance of entities and retain the entities that represent a certain percentage of variability in factor loadings. Communality measures the percentage of variance in a given variable explained by all factors. It is calculated by summing the squares of each entity's loadings in each factor. We calculated the communalities of each entity for 60, 80, 90 and 100 factors, which turned out to be 88%, 82%, 78%, and 76% respectively. Since there is no standard practice for what communality values to choose the optimal number of factors to discuss, and also because the values of the different factors were within reasonable range, we aim to eliminate nearly 20% of the entities. Based on these criteria, we chose 90 factor for discussion. 78% of the terms covered more than 94% of the variance for the 90 factor solution. The entities with communality value lower than the average were removed from the initial t–d matrix. At the end of term reduction process a final 2656 × 975 raw t–d matrix was generated for further steps of LSA. The summary of term reduction process is presented in Table 5.

3.4. Calculating term frequency–inverse document frequency (TF–IDF), SVD and factor loadings

The 2656 × 975 raw t–d matrix was transformed with weighting and normalization methods. Term frequency (tf) and inverse document frequency (idf) values of each entity were calculated consecutively [24,30,31]. The tf–idf value of each entity represents how important that entity is to a document collection or corpus. The tf–idf values increase with the increase in the occurrence of the entity. However, as a counterbalance to this increase, the frequency of the word in the corpus helps to account for the fact that some entities are more common across the documents than the others [32]. The tf–idf, which is transformed from the raw t–d matrix, was then subjected to SVD to decompose it to term-to-concept matrix, document-to-concept matrix and square roots of eigenvalues (singular values), as concept strengths appearing in descending order. Multiplication of term-to-concept and singular value matrixes gives the factor loadings of terms for each research pattern, and the multiplication of document-to-concept matrix and singular value matrix gives the factor loadings of documents for each research pattern. The maximum number of factors generated in this way is equal to the number of documents (in this study, 975). To assess the principal research areas and the broader research themes, the number of factors is adjusted by reducing the dimension of factor loading matrix. In this study, the principal research areas are identified with the 2, 3, 4, 5, 6, 8 and 12 factor solutions, while detailed research themes are explored with the 90 factor solution.

3.5. Rotation of factor loadings and factor threshold values for research areas/themes

In factor analysis, the rotation of the matrix displays the loadings of variable on factors and simplifies the factor associations. Entities with high loading value in each factor associate with a theme. Through rotation of factor axes, the loading of an entity on one factor is maximized while minimizing its loading on other factors. Thereafter, interpretation of the factor structure becomes easier. In other words, associated high-loading terms and documents of each research pattern are clustered and matched. Varimax rotation [33] was applied to the term and document loadings. To interpret both the term and document factors in the same semantic space, the same rotation matrix that was applied to term loadings was applied to the document loadings as well.

Aggregation level varies for each factor solution. While the number of entities/documents loaded in the two or three-factor solution is high, this number decreases for the ninety-factor solutions. To parse the significant and non-significant entities/documents, an appropriate threshold value should be selected for each factor solution. In traditional factor analysis, fixed threshold values are used to determine the significant variances. These values can be 0.3, 0.4 or 0.5. In LSA, fixed threshold values are not appropriate, because in LSA calculation is performed based on the covariance matrix instead of correlation matrix [25]. To determine the threshold value, a heuristic assumption based on empirical probability distribution was applied. This assumption states: "each article should relate on average, to one topic, therefore, each document should load, on average, on one factor" [28]. For example to define the threshold values of documents for different factor solutions, the loading values of documents in each factor are transformed to a vector from its matrix form; and sorted in descending order. The tail distribution of this vector is generated to define the threshold. Although the distribution graph is quite dense to interpret, for n factor solution, the threshold is defined by retaining the $1/n$ of the loadings. According to this assumption, threshold values for the 2, 3, 4, 5, 6, 8, 12 and 90 factor solutions are calculated as 0.107, 0.119, 0.114, 0.116, 0.120, 0.122, 0.125, 0.136, and 0.159 respectively for document loadings. Documents with factor loading below the related threshold value were eliminated.

3.6. Factor evaluation and research theme labeling

In each factor solution, high-loading entities and documents within the calculated threshold value are grouped with the absolute values of the loadings in descending order. High-loading entities and documents are reviewed together and labeled by the authors individually for convergence for all the factors (2 through 8, 12 and 90 factors). To analyze the evolution of the research areas and themes, the factor solutions and high-loading documents are grouped by beginning and ending of years 2004–2005, 2006–2008, 2009–2011 and 2012–2014.

4. Results and findings

4.1. Summary of factor solutions

Table 6 summarizes the principal research areas at various levels of detail, with the two-factor solution providing clustering of the research areas at the broadest level. The principal research areas are identified with 2, 3, 4, 5, 6, 8 and 12 factors. The number of papers loaded for each factor, grouped according to years, is listed alongside. Factors are numbered and represented as $F_{i.j}$, which refers to the jth factor of i-factor solution. For example F12.4 refers to 4th factor of the 12-factor solution.

After an iterative process, the 12-factor solution was considered optimal to represent the principal research areas. The number of articles associated with each factor shows the importance of the corresponding research area within the corresponding factor. New research areas were derived during the interpretation of factor solutions, and same research areas can be seen in multiple factors. For example "*energy management*" appears across (F5.2) to (F12.2), but the number of high-loading articles reduces accordingly. The popularity of each research area is relative to the factor solution.

Mapping the factor solutions aggregated at different levels shows connections across the different BIM research areas. To detail this

Table 5
Summary of term reduction process.

Step	Term reduction process	Number entities
1	Term occurrence after trigram analysis	153,306
2	Removal of entities which appear in only one document	153,306 − 135,469 = 17,387
3	Canceling trigram analysis	
4	Term occurrence after bigram analysis	64,812
5	Removal of entities which appear in only one, and less than 5 documents	64,812 − 61,371 = 3441
6	Removal of derived tokens from document collection phrases	3441 − 6 = 3435
7	Initial SVD for communality reduction	3435 − 779 = 2656

Table 6
Core research areas for selected factor solutions.

Factor number	Factor label	Distribution of papers				
		2004–14	2014–12	2011–09	2008–06	2005–04
F2.1	Implementation practices	571	54%	37%	9%	1%
F2.2	Design practices	404	48%	39%	12%	1%
F3.1	Implementation practices	402	52%	37%	11%	1%
F3.2	Design practices	256	46%	40%	14%	1%
F3.3	Information standards	316	59%	34%	7%	–
F4.1	Implementation practices	364	57%	38%	5%	1%
F4.2	Energy management	127	53%	40%	7%	–
F4.3	Design practices	241	47%	37%	16%	1%
F4.4	Information standards	244	55%	34%	10%	1%
F5.1	Implementation and adoption	338	52%	38%	9%	1%
F5.2	Energy management	101	51%	46%	4%	–
F5.3	Design practices	203	45%	36%	18%	1%
F5.4	Information standards	172	54%	34%	11%	2%
F5.5	Safety management	161	60%	34%	6%	–
F6.1	Implementation and adoption	306	54%	37%	9%	1%
F6.2	Energy management	98	51%	45%	4%	–
F6.3	Architectural design	185	47%	35%	17%	1%
F6.4	Information standards	103	53%	34%	12%	1%
F6.5	Safety management	126	57%	38%	5%	–
F6.6	Information management	156	56%	33%	10%	1%
F8.1	Implementation and adoption	241	54%	37%	8%	1%
F8.2	Energy management	95	52%	44%	4%	–
F8.3	Architectural design	167	47%	32%	20%	1%
F8.4	Information standards	97	52%	33%	13%	2%
F8.5	Safety management	68	60%	38%	2%	–
F8.6	Information management	135	58%	33%	9%	1%
F8.7	Construction and project management	132	56%	39%	5%	–
F8.8	Design and conformance	40	48%	50%	3%	–
F12.1	Implementation and adoption	220	58%	38%	4%	–
F12.2	Energy management	83	51%	45%	5%	–
F12.3	Academy and industry training	113	54%	30%	15%	1%
F12.4	Information exchange and interoperability	81	52%	33%	14%	1%
F12.5	Safety management	46	62%	34%	4%	–
F12.6	Urban/building space design and analysis	62	53%	36%	10%	2%
F12.7	Construction and project management	42	57%	36%	5%	2%
F12.8	Design codes and code compliance	29	52%	45%	3%	–
F12.9	As-is, as-built data	46	65%	28%	7%	–
F12.10	Promotion and TECHNOLOGY DEVELOPMENT	33	64%	30%	6%	–
F12.11	Maintaining and managing facilities	87	55%	36%	9%	–
F12.12	Architectural design process	132	46%	37%	16%	1%

mapping across broader and specific research themes, the findings from the 90-factor solution are presented in Table 8.

Since the 12-factor solution was deemed optimal for principal research areas, and 90-factor solution gives more specific research themes, a cross-loading analysis was performed to establish the interrelation between the 12-factor and 90-factor solutions. Cross-loading indicates how strongly an item in a low-aggregated factor solution, loads on two or more factors on another highly-aggregated factor solution. [34] refer 0.32 as the minimum loading value (threshold) for two or more factors to be considered in cross-loading.

4.2. The principal BIM research areas

As shown in Table 6, at the broadest level, the principal BIM research areas are clustered around *implementation* (F2.1) and *design issues* (F2.2). These research areas emphasize implementation of BIM technology and processes across a wide range of topics, and issues pertaining to BIM-supported design, design integration, and design education respectively.

During the 3-factor solution, implementation (F3.1) and design issues (F3.2) remained stable, while *information standards* (F3.3) emerged as the third principal research area, focusing on issues such as interoperability, data exchange, and BIM applications for different stakeholders.

Similarly, the principal research areas to emerge from the results of the fourth, fifth, sixth and eighth factors relate to *energy management* (F4.2), *adoption* (F5.1), *safety management* (F5.5), *information management* (F6.6), *construction and project management* (F8.7) and *design and conformance* (F8.8) respectively.

The 12-factor solution further expands the principal research areas. During 2004–2005, *architectural design process* (F12.12, F12.6), *training* (F12.3), *project management* (F12.7) and *information exchange* (F12.4) were dominant BIM research areas. This pattern is explicable, because training for BIM-based design and design tools was the critical first step. *Information exchange and interoperability* (F12.4) emerged as another principal area, related to technology maturity, standardization and interdisciplinary exchange of data. While these research areas increased their popularity through 2006–2008, new research themes such as *adoption* (F12.1), *energy management* (F12.2), *urban/building space design and analysis* (F12.6), and *facilities management* (F12.11) have appeared. From 2009 onwards, the additional principal research areas that emerged focus on *safety management* (F12.5), *urban/building space design and analysis* (F12.6), *construction and project management* (F12.7), *code checking and compliance* (F12.8), *as-built data* (F12.9), and *technology management* (F12.10) (Fig. 1). Selected top five high-loading articles for each factor of the 12-factor solution, are presented in Table 7.

In summary, the labels of the 12-factor solution can be grouped under four main BIM research streams that include: (1) Implementation through various phases of project lifecycle, (2) BIM education and training for students as well as professionals, (3) BIM-based design and analysis, and (4) BIM technologies to facilitate information exchange and interoperability.

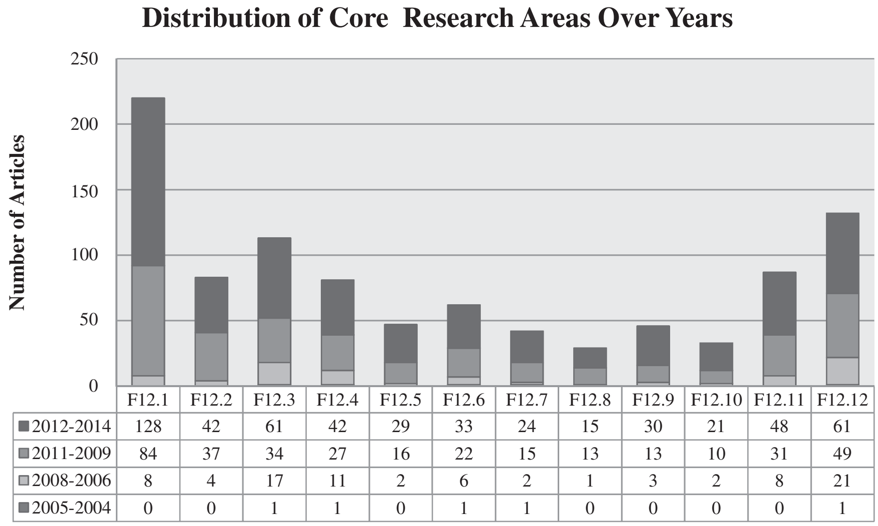

Fig. 1. Distribution of core research subjects.

The patterns observed in the principal research themes identified through LSA, Fig. 1, conform to the historical development of BIM. The terminology BIM was popularized around 2004, especially by software vendors who claimed to be offering new design tools. Thus, leading commercial BIM software and their effects on architectural design process were the focus of early discussion, and have evolved into specific design issues. With time, it was realized that BIM is more than a design tool, and it could have implications on aspects such as energy management, maintenance and facilities management, which were themes closely related to the lifecycle aspect of construction projects. However, at the same time critical challenges to implementing BIM in practice were observed, especially in terms of realizing its potential as a tool that could be used for managing various aspects of the project lifecycle. Consequently, issues relating to BIM implementation including BIM case studies, development of guidelines, regulations and best practices, and challenges to BIM adoption and change management have been the focus of BIM development, with various initiatives of national and global scales being adopted across different parts of the world. Amidst these challenges to achieving higher level of BIM adoption and usage, the number of proprietary BIM applications as well the effort on open source BIM development has gained momentum, with interoperability between BIM tools remaining a fairly consistent topic. All through this period the interest and focus on BIM education have been growing steadily.

4.3. Detailed BIM research themes

The 90-factor analysis, revealed detailed BIM research themes as seen in Table 8 with the percentage distribution of the specified year intervals. The distribution of high-loading articles in Table 8 indicates that *BIM education and curriculum development* (F90.14) remains the most popular research theme in the 90-factor analysis, consistent with the findings in the 12-factor analysis. Selected high-loading articles in the 90-factor solution report experiences and findings from BIM teaching at the undergraduate and graduate levels [89], educational perspective on CAD to BIM transition [90], implementation of BIM in architectural education [91], and course development to address the gaps in professional skills of AEC graduates [92]. While *BIM education and training* remained a fairly popular theme all through, it showed a significant jump between 2012–2014.

Two other notable research themes to emerge through the 90 factor solutions include *energy management and performance assessment* (F90.2) with 43 articles and *building energy performance simulation* (F90.68) with 26 articles. These relate to the *energy management* (F12.2) research area in the 12-factor analysis, which was significant with 83 high-loading papers, and with trends showing the numbers increasing through the studied periods. The selected high-loading articles of these themes focus on minimization of building energy consumption, improving building design with BIM for energy savings [42] and cost optimization [93], energy performance of new and existing buildings [40], accuracy of building energy simulations [41], and green simulations and analysis [94]. These energy related BIM research themes have seen a significant increase since 2010.

With increasing BIM usage and the expansion of BIM capabilities, *IFC standard for interoperability and data exchange* (F90.4) remains another popular theme, with a constant increase in related publications through the studied period. Related high-loading papers focus on topics such as algorithms for IFC-based information exchange [47], IFC-based cost estimation [51], automated querying of IFC-based information [49], and IFC for different use cases [95].

Project collaboration (F90.24) is another significant theme in the 90-factor solution, reinforcing process and organizational aspects of BIM. Besides the high number of related articles all through, the numbers have increased significantly in the last two years. The related high-loading papers focus on issues such as technical requirements for BIM collaboration [96], effects of virtual workspaces on collaboration [97], strategies for BIM-supported collaboration [98], and framework and technologies for multi-disciplinary stakeholders [99].

The 90-factor analysis also reveals research themes associated with *construction management tasks*, *design and analysis*, *technology integration*, *lifecycle information management*, etc. Factors linked to issues such as *safety management* (F90.5), *sustainable design* (F90.45), *as-built data* (F90.9), *cost estimation* (F90.15), *code checking* (F90.6), *scheduling*

Table 7
High loading papers for 12-factor solution.

Factor	Factor labels	High-loading papers
F12.1	Implementation and adoption	[11,35–39]
F12.2	Energy management	[40–44]
F12.3	Academy and industry training	[11,36,45,46]
F12.4	Information exchange and interoperability	[47–51]
F12.5	Safety management	[52–56]
F12.6	Urban/building space design and analysis	[57–61]
F12.7	Construction and project management	[51,62–65]
F12.8	Design codes and code compliance	[66–70]
F12.9	As-is, as-built data	[71–75]
F12.10	Promotion and technology development	[59,76–79]
F12.11	Maintaining and managing facilities	[11,80–83]
F12.12	Architectural design process	[84–88]

Table 8
Factor labels and number of papers of 90-factor solution.

Factor number	Factor label	Distribution of papers				
		2004–14	2014–12	2011–09	2008–06	2005–04
F90.1	Construction industry adoption	23	74%	17%	9%	–
F90.2	Energy performance assessment	43	54%	42%	5%	–
F90.3	Architectural design and design decision making	17	47%	35%	18%	–
F90.4	IFC standard for interoperability and data exchange	38	50%	40%	11%	–
F90.5	BIM for identification of safety hazards and site safety	25	52%	44%	4%	–
F90.6	Automated code compliance checking	18	50%	50%	–	–
F90.7	Lessons learned from the implementation of BIM	9	56%	44%	–	–
F90.8	BIM for solving drawing problems	3	100%	0%	–	–
F90.9	As-is BIMs and as-built data creation via laser scanning	21	67%	29%	5%	–
F90.10	Promotion and development of BIM	14	71%	14%	14%	–
F90.11	FM and healthcare building design	12	50%	50%	–	–
F90.12	Benefits and implementation of cloud computing for BIM	13	75%	25%	–	–
F90.13	Bridge design and construction	9	56%	44%	–	–
F90.14	Teaching BIM and education curriculum development	42	62%	24%	14%	–
F90.15	Construction cost estimation	19	58%	26%	16%	–
F90.16	Urban planning and design development	12	75%	25%	–	–
F90.17	Space design and Space Syntax analysis	6	17%	83%	–	–
F90.18	Interaction of BIM with people and work process	3	67%	33%	–	–
F90.19	BIM and RFID tags for tracking and monitoring	10	30%	60%	10%	–
F90.20	BIM with semantic web technologies	10	50%	20%	30%	–
F90.21	Impact of BIM on design creativity and innovation	7	86%	14%	–	–
F90.22	BIM-based space models to increase the usability of data	9	44%	56%	–	–
F90.23	BIM for building maintenance	6	67%	33%	–	–
F90.24	BIM based project collaboration	26	46%	35%	15%	4%
F90.25	BIM-supported structural analysis and design	10	40%	40%	10%	10%
F90.26	Virtual exploration of physical space	15	60%	27%	7%	7%
F90.27	Sensor technology with BIM to monitor building energy and environment	3	67%	0%	33%	–
F90.28	BIM as an information platform for fabricated materials	2	100%	0%	–	–
F90.29	Virtual BIM models for workspace management	5	80%	20%	–	–
F90.30	BIM at pre-design phase	7	29%	43%	29%	–
F90.31	Generation of parametric models via using point cloud data	6	50%	33%	17%	–
F90.32	Interoperability with BIM-based product data models	8	38%	50%	13%	–
F90.33	BIM-based model transformation among different design models	4	75%	25%	–	–
F90.34	Construction progress monitoring	12	50%	42%	8%	–
F90.35	Development BIM standards	6	50%	50%	–	–
F90.36	BIM for reinforced concrete structures	11	70%	20%	10%	–
F90.37	Retrieval and querying of BIM-based information of various cases	5	60%	40%	–	–
F90.38	Benefits of BIM approach for construction contractors	11	73%	27%	–	–
F90.39	Building energy performance assessment	7	43%	57%	–	–
F90.40	BIM and integrated project delivery (IPD) method	14	64%	36%	–	–
F90.41	BIM with GIS data models	8	25%	50%	25%	–
F90.42	Parametric object modeling development for existing buildings	12	42%	33%	25%	–
F90.43	BIM for different phases of building lifecycle management	16	35%	30%	30%	–
F90.44	Impact of BIM industry (social) and project (technical) networks	8	50%	50%	–	–
F90.45	BIM for sustainable building design	23	52%	44%	4%	–
F90.46	BIM with game technology to visualize user activity	6	17%	67%	17%	–
F90.47	BIM in geospatial information management and 3D urban city modeling	7	57%	29%	14%	–
F90.48	BIM for customized design process	9	44%	33%	22%	–
F90.49	BIM in legal issues	3	100%	0%	–	–
F90.50	Strategy planning for various cases	4	50%	50%	–	–
F90.51	Common needs, practices and challenges of ICT developments in AEC industry	15	67%	20%	7%	7%
F90.52	BIM for On-site information retrieval and visualization	8	63%	38%	–	–
F90.53	Estimation and planning of renovation works	3	67%	0%	33%	–
F90.54	Carbon emission analysis	4	75%	25%	–	–
F90.55	Construction product supply-chain	9	78%	22%	–	–
F90.56	BIM in design of high-rise buildings	4	75%	25%	–	–
F90.57	Benefit realization of BIM implementation for asset owner	12	100%	0%	–	–
F90.58	BIM and ICT systems to optimize HVAC system performance	3	100%	0%	–	–
F90.59	BIM for MEP design coordination	11	36%	55%	9%	–
F90.60	User/client and designer interaction enhancement via BIM models	12	83%	17%	–	–
F90.61	Benefits of BIM architectural design and pre-design phases	10	30%	30%	40%	–
F90.62	Effects of BIM to reduce the design errors	7	43%	57%	–	–
F90.63	Change of thinking and adaptation after BIM for design and construction	3	0%	100%	–	–
F90.64	BIM for quantity takeoff	6	100%	0%	–	–
F90.65	Ontology-based BIM modeling for semantically reasoning of information	14	50%	43%	7%	–
F90.66	BIM for construction project scheduling	18	50%	50%	–	–
F90.67	Virtualized risk analysis and management system	6	50%	50%	–	–
F90.68	Energy performance simulation	26	62%	31%	8%	–
F90.69	Information exchange and interoperability within BIM tools	11	36%	46%	18%	–
F90.70	BIM Design Framework to Support Varied Design Process	16	38%	38%	25%	–
F90.71	BIM implementation in different countries AEC industry	8	50%	50%	–	–
F90.72	Space network layout extraction from graph-based spatial models	6	50%	33%	17%	–
F90.73	Building interior utility design and simulation	12	67%	25%	8%	–
F90.74	BIM for performance-based design within various domains	4	50%	50%	–	–

Table 8 (*continued*)

Factor number	Factor label	Distribution of papers				
		2004–14	2014–12	2011–09	2008–06	2005–04
F90.75	Transition from CAD to BIM	17	24%	24%	35%	18%
F90.76	Automatic detection and conversion of point cloud data to parametric models	6	67%	17%	17%	–
F90.77	Processing and management of BIM spatial data	7	71%	29%	–	–
F90.78	Parametric modeling and design	12	42%	33%	25%	–
F90.79	BIM for lean construction	13	69%	31%	–	–
F90.80	Opportunities and challenges of BIM implementation in construction industry	5	40%	60%	–	–
F90.81	Querying and semantic relations of spatial BIM data	14	50%	43%	7%	–
F90.82	Contribution of BIM to non-value added construction activities	7	57%	43%	–	–
F90.83	Analysis and clustering of 3D BIM-derived geometric data	6	67%	17%	17%	–
F90.84	Standards and guidelines for systematic approach of BIM implementation	5	40%	40%	20%	–
F90.85	Evaluation of BIM function competencies for various stage of project	8	38%	63%	–	–
F90.86	BIM for generative modeling	6	67%	33%	–	–
F90.87	Application and adoption problems of construction enterprises to BIM technology	7	71%	29%	–	–
F90.88	BIM-based systems for navigation purposes	6	100%	0%	–	–
F90.89	Functions of BIM to select implementation strategies	5	80%	20%	–	–
F90.90	BIM process for communication and information management tool	6	67%	33%	–	–

(F90.66), *design decision making* (F90.3), *adoption and change management* (F90.75), and *building lifecycle management* (F90.43) are seen across a number of studies.

4.4. Comparison of principal research areas and research themes

In this section, a semantic link between the papers, the 12 principal research areas and the 90 research themes is established via cross-loading of high-loading papers. Links are presented with the selected high-loading papers in Table 9.

4.4.1. Implementation and adoption (F12.1)

Based on the 12-factor solution *implementation and adoption* (F12.1) is the most trending principal area, with maximum number of high-loading papers. As seen in Table 9, 17 research themes from the 90-factor analysis match up with this principal area, including *adoption* (F90.1) [100,101], *project collaboration* (F90.24) [97,102], *promotion and development* (F90.10) [103] and *education and curriculum development* (F90.14) [46], *cloud computing* (F90.12) [104,105,107], *cost estimation* (F90.15) [51,106], and *product supply chain* (F90.55) [107] since 2008; and, topics such as *integrated project delivery (IPD)* (F90.40) [108,109], *lean construction* (F90.79) [110] and *impact on industry and project networks* (F90.44) [111]. Other research themes focusing on *benefits for construction contractors* (F90.38) [112] and *asset owners* (F90.57) [37,113] have re-emerged as trending topics since 2012.

In summary, BIM implementation and adoption research shows three distinct trends. The first trend is focused on the adoption and implementation processes, and the associated challenges. The second trend is focused on BIM implementation related project delivery and management practices such as IPD and lean construction. The third trend is focused on benefit realization of BIM for different stakeholders, with initial studies focusing on contractors', and increasingly on asset owners.

4.4.2. Energy performance and simulation (F12.2)

Five research themes in the 90-factor solutions matched up with the principal research area of *energy performance and simulation* (F12.2), including the themes focusing on *energy performance assessment* (F90.2 and F90.39) [114,115] and *energy performance simulation* (F90.68) [41]. Other related themes include *performance optimization of HVAC systems* (F90.58) [116] and *building lifecycle management* (F90.43) [42]. While the number of papers on this research area was considerably low before 2010, since then there is a significant increase in these topics.

In summary, energy performance assessment and simulation have become increasingly popular research topics. Another emerging trend is the research on performance assessment/optimization of specialized building systems such as HVAC.

4.4.3. Academy and industry training (F12.3)

Academy and industry training (F12.3) research area matched up with many direct and indirect themes such as *architectural design and decision making* (F90.3) [117], *IPD* (F90.40) [118], *BIM technology development and promotion* (F90.10) [103], *impact of BIM on creativity and innovation* (F90.21) [84], and *changes in implementation and design process* (F90.78) [119]. The research themes about *virtual exploration of physical space* (F90.26) [120] and *game technology to visualize user activity* (F90.46) [121] are matched up with other principal research areas as well. The numbers indicate this as another trending area.

4.4.4. Information exchange and interoperability (F12.4)

Information exchange and interoperability (F12.4) is a principal BIM research area in which IFC is the most-widely discussed topic (F90.4) [50,51] since 2004, and still remains a trending topic, with increasing number of articles every year. *Interoperability of BIM applications* (F90.69, F90.47 and F90.70) [47,63,122,123] and *product data models* (F90.32) [124] have also been discussed. *Information retrieval and querying* (F90.37) [125], *cloud computing* (F90.12) [104], *semantic reasoning* (F90.65) [126] and *semantic web technologies* (F90.20) [127] in BIM are other related themes that matched-up. Emerging themes in this research area include *automatic clustering, association and semantic reasoning of IFC-based information*, for example F90.65 and F90.37, which have emerged since 2010.

4.4.5. Safety management (F12.5)

During 2004–2007 there were no *BIM and safety management* (F12.5) related studies in the corpus, but since then *safety hazards and site safety* (F90.5) [52,56] has emerged as an important research theme. The role of BIM as a virtual design and construction medium to reduce uncertainty, improve safety, identify problems and analyze potential impacts has been discussed. Although the research theme on *project scheduling* (F90.66) [128] is not directly related to safety, these studies predict and simulate the sequence of activities around which safety issues are planned and managed. Similarly, studies on the use of *BIM for workspace management* (F90.29) [129] and *risk analysis and management* (F90.67) [130] relate to safety management. Safety management is also discussed as one of the key *benefits of BIM for contractors* (F90.38) [112].

Table 9
Interrelations between 12 and 90 factor solutions via cross-loading.

F12.#	12-factor labels	F90.#	90-factor labels
F12.1	Implementation and adoption	F90.1	Construction industry adoption
		F90.40	BIM and integrated project delivery (IPD) method
		F90.15	Construction cost estimation
		F90.24	BIM-based project collaboration
		F90.87	Application and adoption problems of construction enterprises to BIM technology
		F90.7	Lessons learned from the implementation of BIM
		F90.10	Promotion and development of BIM
		F90.12	Benefits and implementation of cloud computing for BIM
		F90.14	Teaching BIM and education curriculum development
		F90.16	Urban planning and design development
		F90.57	Benefit realization of BIM implementation for asset owner
		F90.38	Benefits of BIM approach for construction contractors
		F90.44	Impact of BIM industry (social) and project (technical) networks
		F90.55	Construction product supply-chain
		F90.71	BIM implementation in different countries AEC industry
		F90.79	BIM for lean construction
		F90.80	Opportunities and challenges of BIM implementation in construction industry
F12.2	Energy performance and simulation	F90.2	Energy performance assessment
		F90.68	Energy performance simulation
		F90.39	Building energy performance assessment
		F90.43	BIM for different phases of building lifecycle management
		F90.58	BIM and ICT systems to optimize HVAC system performance
F12.3	Academy and industry training	F90.14	Teaching BIM and education curriculum development
		F90.3	Architectural design and design decision making
		F90.10	Promotion and development of BIM technology
		F90.75	Transition from CAD to BIM
		F90.78	Parametric modeling and design
		F90.40	BIM and integrated project delivery (IPD) method
		F90.21	Impact of BIM on design creativity and innovation
		F90.26	Virtual exploration of physical space
		F90.46	BIM with game technology to visualize user activity
F12.4	Information exchange and interoperability	F90.4	IFC standard for interoperability and data exchange
		F90.69	Information exchange and interoperability within BIM tools
		F90.12	Benefits and implementation of cloud computing for BIM
		F90.32	Interoperability with BIM-based product data models
		F90.47	BIM in Geospatial information management and 3D urban city modeling
		F90.37	Retrieval and querying of BIM-based information of various cases
		F90.65	Ontology-based BIM modeling for semantically reasoning of information
		F90.20	BIM with semantic web technologies
		F90.70	BIM Design framework to support varied design process
F12.5	Safety management	F90.5	BIM for identification of safety hazards and site safety
		F90.66	Construction project scheduling
		F90.38	Benefits of BIM approach for construction contractors
		F90.19	BIM and RFID tags for tracking and monitoring
		F90.29	Virtual BIM Models for workspace management
		F90.67	Virtualized risk analysis and management system
F12.6	Urban/building space design and analysis	F90.16	Urban planning and design development
		F90.81	Querying and semantic relations of spatial BIM data
		F90.41	BIM with GIS data models
		F90.47	Geospatial information management and 3D urban city modeling
		F90.17	Space design and space syntax analysis
		F90.65	Ontology-based BIM modeling for semantically reasoning of information
		F90.26	Virtual exploration of physical space
		F90.44	Impact of BIM industry (social) and project (technical) networks
		F90.22	BIM-based space models to increase the usability of data
		F90.60	User/client and designer interaction enhancement via BIM models
F12.7	Construction and project management	F90.15	Construction cost estimation
		F90.13	Bridge design and construction
		F90.34	Construction progress monitoring
		F90.36	Reinforced concrete structures
F12.8	Design codes and code compliance	F90.6	Automated code compliance checking
		F90.5	BIM for identification of safety hazards and site safety management
		F90.33	BIM-based model transformation among different design models
F12.9	As-is, as-built data	F90.9	As-is BIMs and as-built data creation via laser scanning
		F90.31	Generation of parametric models via using point cloud data
		F90.42	Parametric object modeling development for existing buildings
		F90.34	Construction progress monitoring
		F90.76	Automatic detection and conversion of point cloud data to parametric models
F12.10	Promotion and technology development	F90.10	Promotion and development of BIM
		F90.14	Teaching BIM and education curriculum development
		F90.19	BIM and RFID tags for tracking and monitoring
		F90.16	Urban planning and design development
		F90.75	Transition from CAD to BIM
		F90.20	BIM with semantic web technologies
F12.11	Maintaining and managing facilities	F90.11	FM and healthcare building design

Table 9 (*continued*)

F12.#	12-factor labels	F90.#	90-factor labels
		F90.19	BIM and RFID tags for tracking and monitoring
		F90.57	Benefit realization of BIM implementation for asset owner
		F90.23	BIM for building maintenance
		F90.33	BIM-based model transformation among different design models
		F90.65	Ontology-based BIM modeling for semantically reasoning of information
		F90.37	Retrieval and querying of BIM-based information of various cases
		F90.7	Lessons learned from the implementation of BIM
		F90.30	BIM at pre-design phase
F12.12	Architectural design process	F90.78	Parametric modeling and design
		F90.3	Architectural design and design decision making
		F90.16	Urban planning and design development
		F90.30	BIM at pre-design phase
		F90.60	User/client and designer interaction enhancement via BIM-based models
		F90.33	BIM-based model transformation among different design models
		F90.75	Transition from CAD to BIM
		F90.13	Bridge design and construction
		F90.17	Space design and Space Syntax analysis
		F90.26	Virtual exploration of physical space
		F90.70	BIM design framework to support varied design process
		F90.46	BIM with game technology to visualize user activity
		F90.73	Building interior utility design and simulation
		F90.45	BIM for sustainable building design

4.4.6. Urban/building space design and analysis (F12.6)

Though there are no studies in the BIM corpus on *urban/building space design and analysis* until the end of 2007, since then many articles have been published in this area, especially around themes such as *urban planning and design* (F90.16) [131,132] and *integration with GIS* (F90.41) [133]. *Space design and syntax analysis* (F90.17) [61] and *usability through spatial models* (F90.22) [58] are related research themes that matched up during the cross-factor analysis. The research themes focusing on *semantic technologies for BIM* (F90.81, F90.65) also factored with F12.6. The increasing number of articles about these themes can be considered a noteworthy future trend in this research area. *User/client requirements and interaction* (F90.60) [134] is another important theme identified in this area, with a significant increase in related articles during 2012–2014.

4.4.7. Construction and project management (F12.7)

The cross-factor analysis shows four research themes that matched up with the construction and project management research area. While there are some studies about *construction progress monitoring* (F90.34) [135] and specific use cases such as *bridge design* (F90.13) [63] and *reinforced concrete structures* (F90.36) [136], majority of studies in this area are focused on *quantity takeoff and cost estimation* (F90.15) [51,106], with increasing numbers through the years.

4.4.8. Design codes and code compliance (F12.8)

Three research themes matched up with *design codes and code compliance* as the principal research area. *Automated code checking* (F90.6) [67,70] emerged as the dominant theme in this area. While there are no related studies in the corpus during 2004–2007, the numbers have been increasing since then. The research themes on *model transformation across different design models* (F90.33) [137] and *identification of safety hazards* (F90.5) [52] also matched up with code checking and compliance.

4.4.9. As-is, as-built data (F12.9)

The principal research area labeled as *as-is, as-built data* (F12.9) is found to match-up with five research themes in the 90 factor solution, with the use of *laser scanning for as-built data* (F90.9) [73,138] as the main research theme. The use of as-built data for specific purposes such as *construction progress monitoring* (F90.34) [135] is another emerging topic. In addition, *developing parametric object models from laser scanned as-built data* appears across three research themes (F90.31, F90.42 and F90.76) [71,135,139], indicating an emerging research area topic since 2012.

4.4.10. Promotion and technology development (F12.10)

In the cross factor analysis, six research themes matched-up with *promotion and development of BIM technologies* (F90.10) [103]. The research themes about *education and teaching* (F90.14) [89], *urban planning* (F90.16) [86], *transition from CAD to BIM* (F90.75) [90], *integration with RFID*, and *semantic web technologies* (F90.20) [127] also matched-up with promotion and development of BIM technologies.

4.4.11. Maintaining and managing facilities (F12.11)

Several research themes matched up with maintaining and managing facilities (F12.11). *Healthcare facilities* (F90.11) [83,140] was found to be the most studied case in this research area. Other research themes to emerge since 2012 focus on *lessons learnt from BIM implementation for maintenance* (F90.7) [39] and *benefits of BIM for asset owners* (F90.57) [37]. In addition, the research on BIM for facilities management and maintenance is concerned with the generation, specification and management of required information, as reflected in the associated research themes of *model transformation among different processes* (F90.33) [137], *information retrieval and querying* (F90.37) [125] and *semantic reasoning of BIM-based information* (F90.65) [130]. Similarly, the theme *implementation of BIM at pre-design phase* (F90.30) [85] emphasizes generation of information for facilities management from the early phases of project lifecycle.

4.4.12. Architectural design process (F12.12)

The principal research area labeled *architectural design process* (F12.12) matched up with research themes such as *BIM for urban design* (F90.16) [86], *bridge design and construction* (F90.13) [63] and *sustainable building design* (F90.45) [141]. Research themes focusing on *virtual exploration of physical space* (F90.26) and *building utility design and simulation* (F90.73) [57] also emphasize the role of BIM in the design process. Similarly, the research themes on *parametric modeling and design* (F90.78) [103] and *transition from CAD to BIM* (F90.75) [90] focus on BIM-based design processes. Other themes related to BIM for design include *implementation strategies* (F90.3 and F90.70) [123], user *behavior and interaction* (F90.60) [70], and *game technology for visualization* (F90.46) [121].

In summary, the identified themes in the architectural design process research area can be grouped under five topics that include: (1) changes in traditional design, (2) design for different domains, (3) design decision making, (4) visualization and (5) client/user interaction. The significant increase in the number of articles related to user/client and designer interaction (F90.60) and sustainable building design (F90.45) during 2012–2014 is particularly noteworthy.

5. Limitations of the study

The revealed research areas and themes provide the patterns in BIM research. Nonetheless, the following limitations of this research need to be considered while reviewing the findings.

First, we used only "building information modeling" and "bim" phrases in titles, abstracts and keywords of the publications through data collection. There may be some other publications which are about BIM but do not include the specified phrases in their abstracts, titles or keywords. To overcome this limitation, we run the second round through document collection by searching and "building information modeling" and "bim" phrases together in full text and 89 more abstracts were added. However, the decision to add the related publication into the corpus is based on researcher's interpretation. Similarly, there may be some other set of keywords that could have been used to form the corpus such as "product/process modeling", "ontologies/taxonomies/lexicons on buildings/facilities" or "information representation for construction". However, in general it was considered safe to assume that BIM related papers during the studied period (2004–2014) will have some reference to the keywords and phrases used in this research.

As the result of this analysis, some of the high-loading papers for core research subjects are selected and presented. However, the loading values of selected papers neither reflect an academic value nor represent the number of citations of them in BIM literature. The methodology applies the number of occurrences of each term in each abstract through the entire corpus and calculates the loading values. Therefore, the high-loading papers in this research should not be considered as the most popular ones associated with the research area/theme.

Other limitations are related to the methodology of this study. The high-loading terms and articles are determined with respect to a threshold value. We calculated variances of term and document loadings to specify the threshold and select the terms and documents which have a bigger loading value than the threshold. This calculation estimates the statistically optimum threshold value for term and factor loadings. However, it does not mean that the terms and documents which have a loading value below the threshold are not related with the associated factor. In other words a lower threshold value increases the number of selected terms and documents. In addition, we used abstracts of the publications instead of the full text. This can be considered as a limitation due to ignoring the rest of the information. However, the derived entities (word/word groups) specifically from the literature review and methodology sections of publications increase the noise data and make the computer supported analysis more difficult. Besides, the factor labeling was done by researchers which may cause the discussions about subjectivity as a limitation of this study. However, to address this limitation, the factor labeling was independently done by the authors of this paper and then put together.

6. Future research and conclusions

This research sought to investigate the patterns and trends in BIM research by systematically analyzing the abstracts of 975 articles to empirically identify the key research areas and themes. The main contribution of this paper is the analytical decomposition and interpretation of the body of BIM research into twelve principal research areas, while revealing the expansive variety of the discipline with ninety substantial research themes. Through a cross-factor analysis, this research also presents the links between the principal research areas and the corresponding themes, drawing a map of BIM research structure.

This analysis establishes an objective and empirical foundation for the future discussion about the structure of BIM research. The identified research areas and themes indicate trends and future opportunities, which can be utilized by the industry as well as academia. More practically, the results of this study facilitates the existing BIM researchers to discover the position of their research studies within a broader and detailed frame; and the new researchers to understand the nature of BIM research and assess their areas of interest for their potential research with the corresponding research trend.

We revealed twelve main research areas with associated detailed research themes in this study. For potential further studies, researchers can pick one or more research areas and make another analysis with the same or another methodology. Researchers used LSA for this study. However, there are other statistical factor analysis methods which can be applicable to this research. For future studies, the researcher can apply another method to a similar collection to see the affinity and diversity of research subjects and themes with associated articles. To increase the application areas of this research, a dynamic query system can be developed with the same corpus by applying similar methodologies.

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