AUTOMATED COMPLIANCE CHECKING IN THE AEC INDUSTRY: A REVIEW OF CURRENT STATE, OPPORTUNITIES AND CHALLENGES

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ABSTRACT

Automated Compliance Checking (ACC) is continuously gaining traction in improving the efficiency and precision in regulatory compliances within the AEC sector. Thus, this research presents a comprehensive review of the current state of ACC emphasising its application domains, techniques, challenges and opportunities. The review reveal that ACC is currently being applied in multiple domains including building design analysis, energy efficiency, construction safety and fire safety. ACC systems currently employ techniques such as artificial intelligence (machine learning, neural networks, and natural language processing), graph-based methods, semantic enrichment and representation and general rule representation analysis. The review identifies technological constraints and integration difficulties as main challenges facing ACC implementation. The potential opportunities for ACC include integration with enhanced technologies, expanding application domains, collaborations and standardisations. This study addresses existing knowledge gaps and enhances the understanding of ACC's role and impact, steering future research towards innovative approaches and improved implementation strategies.

Keywords: Automated Compliance Checking (ACC); Architecture, Engineering, and Construction (AEC); review; challenges; opportunities

INTRODUCTION

Design, procurement and construction are guided by codes and regulations that protect lives and properties. The use of these codes is not new in construction, with the Code of Hammurabi (2000 BCE) focusing on legal codes regulating construction liability, Ebers Papyrus (2750 BCE) focusing on regulations relating to housing and sanitation, and City-states like Athens (500 BCE) containing codes regulating construction techniques and building materials (Brasil, 2024). These codes are critical in ensuring the safety of the lives and properties of building users and owners. For example, the Code of Hammurabi states that "if a contractor constructs a residence for an individual and fails to execute the work adequately, resulting in the collapse of the structure and the death of its owner, the contractor shall face the penalty of death" (Heady, 2012). Failing to abide by the codes and regulations guiding the design, procurement and construction of buildings can result in severe consequences, like loss of lives and properties of building owners.

Several issues have been linked to a lack of adherence to codes and regulations guiding the design, procurement and construction. This is well captured in the report that ensued as a result of the catastrophic Grenfell Fire of 2017 in the UK which claimed 71 immediate lives. The severity of the damages resulting from the fire was attributed to a lack of adherence and ignorance of the safety regulations (Hackitt, 2018). In addition to the loss of lives, the United States recorded an estimated property damage of approximately $15.9 billion in the year 2021 alone (NFPA, 2021). Failure to comply with regulatory guidelines also leads to project redesign, rework, and financial losses, which typically require intricate, time-intensive, and expensive solutions. This ultimately results in construction disputes, conflicts and eventual project failure (Walsh, 2017). This stresses the need to ensure building delivery conforms with established codes and regulations (Zhang et al., 2023). Therefore, the relevance of the compliance checking process cannot be overemphasised. The process engages the expertise of diverse stakeholders, including designers, professionals with subject matter expertise, and regulatory experts.

The traditional approach to compliance checking, which is conducted manually, has been linked to poor project performance and delays (Macit İlal & Günaydın, 2017). This leads to inefficient outcomes, including inaccuracies, high costs and timewasting (Han et al., 1998; Macit İlal & Günaydın, 2017). This can be linked to failures in existing approaches including a lack of a comprehensive audit trail and inadequate quality assurance measures (Hackitt, 2018). These deficiencies support unclear delineation of roles and responsibilities, disregard for quality assurance, and ineffective enforcement of existing regulations (Hackitt, 2018). These insights form the basis for the call for a transition to a more reliable approach to support compliance with codes and regulations including digital solutions for compliance checking (Caplehorn, 2013; Hackitt, 2018).

The need for digital solutions to facilitate improved compliance checking prompted experts to develop various Automated Compliance Checking (ACC) systems, based on semantic and ontology bases (Beach et al., 2015; Macit İlal & Günaydın, 2017; Wu et al., 2021; Zheng et al., 2022; Zhou et al., 2022), language-models (Sydora & Stroulia, 2020), hard-codes (Jiang & Leicht, 2015), object-orientation (Doukari et al., 2022; Garrett & Hakim, 1992), and logic-rules (Tan et al., 2010; Zhang & El-Gohary, 2017). The developments of these systems have demonstrated numerous advantages of automated compliance checking, including decreased checking time, expenses, and inaccuracies (Salama & El-Gohary, 2013; Tan et al., 2010), as well as enhanced efficiency and accuracy (Beach et al., 2020; Shahi et al., 2019).

Given the established advantages and potential of ACC application in construction, it is imperative to allocate additional research efforts towards furthering its utilisation within the construction sector. Notable studies have been conducted on ACC in the Architecture, Engineering, and Construction (AEC) industry. For example, Nuyts et al., (2024) have explored various approaches for compliance checking of construction data. Similarly, (Amor & Dimyadi, 2021) have examined evolving approaches for automated compliance checking, addressing challenges related to sharing digital architectural and engineering design information, formalising normative provisions as computable rules, and processing them for compliance. (Zhang, Ma, & Broyd, 2023) have also conducted a systematic literature review to identify the challenges affecting the application of rule capture for ACC. Additionally, (Zhang et al., 2022) have conducted a systematic literature review to identify the challenges related to rule interpretation and representation for ACC. While these efforts have made valuable contributions, they have always focused on specific areas of application or system development approach, without covering the end-to-end processes of compliance checking.

The primary aim of this study is to conduct a comprehensive analysis of the current status of ACC within the AEC industry. This analysis adopts a holistic approach and focuses on the areas of ACC application. Furthermore, the study seeks to identify potential opportunities and challenges that future research should address in order to fully exploit the benefits of ACC in the AEC industry. To achieve these objectives, the research first explores the common and relevant application domains of ACC in the AEC industry. This provides a foundation for understanding the various contexts in which ACC is utilised. Additionally, the study presents an updated overview of ACC applications in the AEC industry, taking into account the recent advancements in this rapidly evolving field. Moreover, the study organises the gathered information in a manner that facilitates the linkage and comparison of ACC research across different areas. This structured approach will enable researchers to easily connect their work with related studies and compare them from various domains, thereby paving the way for subsequent investigations in this field. Ultimately, this would enhance future research endeavours within specific areas of interest for individual researchers. Furthermore, the paper will identify specific challenges and opportunities for future research in integrating ACC within the AEC industry. By highlighting these areas, the study aims to guide researchers towards addressing the existing gaps and exploring new avenues for the effective implementation of ACC in the AEC sector.

The structure of the paper is as follows: Section 1 provides background to the study, outlines the objectives of the review and distinguishes it from prior related studies. Section 2 details the methodology employed in the review and discusses the criteria used to sift through the literature. Section 3 presents the findings of the review, with subsections organising the applications according to different construction areas. This is followed by Section 4, which delves into the challenges and opportunities of ACC techniques in construction from a comprehensive standpoint. Lastly, Section 5 offers the conclusion and future directions.

METHODOLOGY

The current study utilised a methodology comprising three steps (Figure 1). The step entailed data collection from the Scopus database, and subsequent bibliometric and in-depth analyses. This approach of using exploratory sequential mixed methods for conducting review has gained considerable traction in the academic community (Weerasinghe et al., 2024). This is due to its demonstrated efficacy in evaluating the current state of the domain being studied (Weerasinghe et al., 2024). The bibliometric analysis quantitatively evaluates the literature and systematically maps extensive datasets using bibliometric analysis. This eventually reveals the important trends and patterns contained in a specific research domain (Wuni et al., 2019), thus, offering critical perceptions into emerging and evolving areas of study. In-depth analysis, on the other hand, facilitates a comprehensive understanding and synthesis of the existing literature.

Figure. 1.

Data collection

Indexed databases play a pivotal role in conducting literature searches, with Web of Science and Scopus being widely acknowledged for their dependability and extensive coverage of scholarly journals and conferences (Dauda & Ajayi, 2022). The search was specifically carried out in Scopus due to its vast array of high-impact articles, current research findings, and comprehensive coverage of articles on the AEC sector, rendering it a valuable resource for similar review studies (Saka et al., 2023; Yamusa et al., 2024a). The search query utilised for the study is presented in Table 1 below. The search query was applied within TITLE-ABS-KEY (i.e. article title, abstract and keywords).

Table 1: Search Query (Source: Authors).

Aspect	Search Query
Technique	“natural language processing”, “artificial intelligence”, “artificial neural network*”, “deep learning”, “deep neural network*”, “semantic*”, “knowledge graph”

Application	"compliance checking", "compliance diagnostic*", "information extraction", "information transformation", "information extraction"
Construction	"construction", "building*"

The search considered some criteria for paper inclusion in the study. The study only focused on works in AEC industry, works that develop/use one or more ACC techniques for an AEC industry-related task, works published in English language and work published in peer-reviewed journals. This is to ensure that the papers used in the review are focused on the aim of the study. The search process concluded in June 2024, yielding a total of 2830 records initially. These records were then exported into MS Excel to facilitate the removal of any duplicate entries. After removing duplicates, a total of 2362 records were employed for the analyses.

Bibliometric analysis

The current research employs bibliometric analysis to evaluate the yearly publication patterns, international collaboration, collaboration between authors and research sources, as well as keyword co-occurrence. This was achieved in two steps: establishing co-authorship, author and document citation, and keywords co-occurrence networks, and generating maps from the networks to generate insights. This aids in the visualisation and identification of trends, patterns, and advancements in the research field (Wuni et al., 2019). The VOSviewer was employed for the bibliometric analysis due to its sophistication, open-source nature, and user-friendliness (Wuni et al., 2019). The 2362 records retrieved from the filtered search were used as the input for the bibliometric analysis.

In-depth analysis

The 2362 records retrieved from the filtered search were further scrutinised for the in-depth analysis. This includes considering some criteria for excluding papers that are not in line with the aim of the study. The study excluded works focusing on areas other than AEC, works using ACC in other non-construction activities, works from non-peer-reviewed journals and industry white papers, conferences and book chapters. This results in 1481 numbers of articles that facilitate insights on how ACC is applied in addressing a construction-related issue and to avert publication bias (Saka et al., 2023). The authors then read through the titles of the 1481 articles to select those directly related to the subject matter. This led to the identification of 185 articles, which the authors read the abstracts. After going through the abstracts, 79 articles were identified for full-text reading. Finally, to cover the most current developments, the timeframe of the papers employed for the in-depth analysis is from 2010 to 2024. This facilitates the identification of the most significant research articles for subsequent evaluation. This is due to the gradual rise in ACC efforts from the year 2010 as evident from the bibliometric analysis result in Figure 2. This is further stressed by the surge in technological research and citations in the construction industry from the year 2010 (Elkhayat et al., 2024).

This process led to the identification of 40 pertinent articles for an in-depth exploration and discourse on key application areas, different ACC tasks, opportunities and challenges in the use of ACC within the AEC industry. The 40 articles were agreed upon by a consensus of the review of three of the authors. The prevailing discourse within the literature was reviewed using in-depth analysis. The in-depth analysis played a crucial role in elucidating the current state of research and identifying gaps in the field of ACC in the AEC industry.

FINDINGS AND DISCUSSION

Bibliometric Analysis Findings

Annual publication trend

A consistent growth in the publication trend of ACC research within the AEC industry can be seen from 1981 to 2024 (June) (Fig. 2). The trend occurred in three distinct phases: the first phase spanning from 1981 to 2002 with a total of 55 published articles, the second phase from 2003 to 2021 with a total of 1040 published articles, and the third phase from 2022 to the present with a total of 1278 published articles. The first phase recorded scanty publications, with no particular year recording up to 10 publications, and some years recording no publication, thus, indicating the early stages of ACC research exploration with a total publication coverage of 2.32%. The second phase saw a gradual publication increase, with occasional minor declines. The second phase covers 43.82% of the total publications. The year 2023 records the highest number of publications of any given year, substantiating the third phase as the phase with the highest number of articles published with a coverage of 53.86% of the total publications. It is also noteworthy that the data for 2024 is only available until June, suggesting the possibility of additional publications by year-end. The upward trajectory in publications since 2003 can be attributed to the developments recorded in the use of ICT within the AEC industry. Given the substantial contribution of ICT to the AEC sector, the developments likely influenced the increase in research and publications on ACC to improve building performance efficiency. For example, some initiatives recommend using digital solutions to improve building safety (Hackitt, 2018). This is in addition to the UK government commissioning a working group to incorporate regulations into Building Information Modelling (BIM) for improved compliance (Caplehorn, 2013). Initiatives like these could be the basis for the surge in ACC research in recent years.

Figure. 2.

Major contributing countries

A network of collaboration among countries (Fig. 3) was established using VOSviewer 1.6.20 to identify the leading countries in ACC research. The top 10 leading countries were identified using the link strength generated by the bibliometric analysis (Table 2). The link strength is also represented by the size of the nodes in the figure (Yamusa et al., 2024a). To determine the leading countries, the "*minimum number of documents*" and the "*minimum number of citations*" were set at five each. This is in line with previous efforts which consider the benchmark of five to be adequate for analysis (Weerasinghe et al., 2024). Out of 109 countries, 55 met the threshold. The results indicate that China, US, South Korea, Australia and India are the top five leading countries in ACC research. This suggests that these countries are making significant efforts towards automating their compliance checking process, to improve the performance of their AEC industry. An analysis of the leading countries in ACC research yields insights into the major countries to engage with. The analysis also serves as a foundation for enhancing collaborative efforts, encouraging academic discourse, and bolstering partnerships within the industry. Furthermore, as research influences practical applications, the inferences from this analysis shed light on the countries and regions that are at the forefront of the ACC applications.

Figure. 3.

Table. 2. Top 10 countries for ACC research collaboration (Source: Authors' findings).

Rank	Country	Number of documents	Citations	Total link strength
1	China	1197	16319	108372
2	United States	313	11720	37879
3	South Korea	105	2144	19744
4	Australia	65	2205	17812
5	India	139	2095	16710
6	United Kingdom	106	3211	16340
7	Hong Kong	68	2053	13207
8	Canada	68	1206	11804
9	Germany	72	2073	11385
10	Saudi Arabia	49	667	8607

Analysis of leading authors

A co-occurrence network of collaboration among authors (Fig. 4) to establish the leading authors in ACC research was also developed. The exchange of knowledge and research proficiency is significantly enhanced by the collaboration among researchers from diverse institutions (Wuni et al., 2019; Yamusa et al., 2024). Consequently, it is essential to conduct a comprehensive analysis of the partnerships among prominent authors in the field of ACC research. Such analysis reveals the leading authors and facilitates the acquisition of substantial grants and funding for research initiatives. The top 10 leading authors were identified and captured in Table 3. The "*minimum number of documents*" and "*minimum number of citations*" were also set at five each to come up with the leading authors. Only 36 out of the 8447 authors met this threshold. Using the total link strength, the results indicate that El-Gohary, N., Zhang, R., Zhou, P., Zhang, J., and Zhong, B. are the five leading authors in ACC research. This indicates that these authors collaborated with several other authors to publish significant studies on ACC research. This analysis provides valuable insights to academics regarding the leading and experienced ACC researchers who may be available for potential future partnerships and collaborations.

Figure. 4.

Table. 3. Top 10 authors for ACC research collaboration (Source: Authors' findings).

Rank	Author	Number of documents	Citations	Total link strength
1	El-Gohary, Nora	13	381	1707
2	Zhang, Ruichuan	5	91	883
3	Zhou, Peng	5	250	845
4	Zhang, Jiansong	10	655	671

5	Zhong, Botao	7	219	560
6	Zhang, Liangpei	9	390	545
7	Li, Heng	6	165	540
8	Luo, Hanbin	6	209	511
9	Du, Bo	5	100	460
10	Lin, Jia-Rui	5	130	417

Analysis of leading research sources

Journals play a crucial role in facilitating the exchange of knowledge among scholars, enabling constructive criticism, expanding ideas, and introducing new theories. This analysis is beneficial for readers as it helps them efficiently identify relevant sources for their studies, while also aiding authors in selecting appropriate journals for submitting their manuscripts (Lecheler & Kruikemeier, 2016; Wuni et al., 2019). The analysis focused on citations and sources for conducting the analysis. After setting the threshold at five for the "*minimum number of documents*" and "*minimum number of citations*", 94 sources out of 703 met the threshold. The outcome of this analysis shows Automation in Construction, Journal of Computing in Civil Engineering, Advanced Engineering Informatics, Applied Sciences, and Sensors to be the leading research sources in the research on ACC application within the AEC industry. Understanding the citations and link strengths of the leading journals in ACC research will assist researchers in selecting appropriate journals for the submission of their articles.

Figure. 5.

Table. 4. Top 10 sources for ACC research publications (Source: Authors' findings).

Rank	Source	Number of documents	Citations	Total link strength
1	Automation in Construction	61	102	3289
2	Journal of Computing in Civil Engineering	23	163	1934
3	Advanced Engineering Informatics	33	1269	1925
4	Applied Sciences (Switzerland)	48	6	1760
5	Sensors	42	963	1631
6	ISPRS Journal of Photogrammetry and Remote Sensing	27	2686	1272
7	IEEE Transactions on Image Processing	18	1157	1198
8	Buildings	17	2861	1090
9	Neurocomputing	24	202	922
10	IEEE Transactions on Pattern Analysis and Machine Intelligence	19	236	849

Co-occurrence analysis of keywords

A network analysis of keywords assists in the identification of primary themes in research articles and their connections (Wuni et al., 2019; Yamusa et al., 2024a). Therefore, the selection of keywords for research articles must be approached with great diligence, grounded in a thorough analysis of the relevant keywords within the research domain. Author-provided keywords are commonly utilised to pinpoint primary research areas. To create the keyword network, the minimum occurrence threshold was set to five by default. This returned 214 keywords out of 6748. This was after merging similar keywords and excluding irrelevant ones (e.g., 'Building Information Modelling' and 'BIM' were merged).

The results reveal that deep learning (372 occurrences), feature extraction (117 occurrences), natural language processing (120 occurrences), information extraction (113 occurrences), and machine learning (103 occurrences) are the top five author keywords. This outcome highlights the focus of ACC research on recent advances in technology including machine learning and deep learning. Therefore, enhancing technological advancements is a key strategy to for improving ACC research. Researchers becoming cognisant of the keywords will inform their selection of relevant keywords in their articles, thereby enhancing the indexing and retrieval of their work across broader platforms.

Figure. 6.

Table. 5. Top 10 co-occurring keywords in ACC research (Source: Authors' findings).

Rank	Keyword	Occurrences	Total link strength
1	deep learning	372	548
2	feature extraction	117	277
3	natural language processing	120	216
4	information extraction	113	204
5	machine learning	103	158
6	ontology	70	130
7	knowledge graph	92	128
8	semantic segmentation	71	128
9	attention mechanism	73	126
10	building extraction	61	91

In-depth Analysis Findings

Automated compliance checking process

The ACC process is summarised by (Eastman et al., 2009), as illustrated in Fig. 7. The process comprises rule representation, BIM model data preparation stage, rule execution and result reporting. Rule representation is the first and most critical phase of the ACC process. It involves a thorough analysis of the standards. The analysis of the standards results in the development of taxonomies (Soliman-Junior et al., 2021; Zhang et al., 2023; Yamusa, et al., 2024b). The outcome from the analysed standards is subsequently translated into rules and encoded in a format that is interpretable by computers (Ma et al., 2024). This results in information text classification (into relevant sentences), information extraction (into relevant sentences tagged with features) and information transformation (into logic clauses) (Zhang & El-Gohary, 2015). However, the rule representation is performed only once for each standard. The next phase is the BIM model data preparation. This is the phase where relevant information is extracted from BIM models in accordance with the established rules, resulting in a curated subset of data. This subset is then reformatted to facilitate inference processes. Next is the rule execution phase, where the previously defined rules derived from the standards in the rule representation phase are applied to the BIM models to conduct specific compliance-checking tasks. Finally, the outcomes of the compliance-checking task are presented to users.

Figure. 7.

Different research efforts have been carried out within the different phases of the ACC process (Fig. 7). These research efforts have been applied to different construction domains to carry out different tasks. Additionally, different technologies have been leveraged to automate some of the ACC tasks and improve the efficiency of compliance checking systems. The focus of this review as initially stated is based on the three major areas including 1) various application domains (e.g., safety management, fire safety, energy efficiency, and design analysis), 2) development techniques and different ACC tasks (such as information extraction and transformation) as presented in Tables 6-8, and 3) challenges and opportunities for ACC in AEC industry. The major findings of the in-depth analysis are therefore categorised based on these areas. The findings show that research spans multiple domains within the construction and engineering industry including construction safety, building design analysis, energy efficiency and fire safety (Table 6).

Table. 6. Application domains in AEC in ACC research (Source: Authors' findings).

Domain	No of studies	References
Construction safety	11	(Beach et al., 2020; Macit İlal & Günaydın, 2017; Melzner et al., 2013; Nuyts et al., 2024; Pan et al., 2022; Shen et al., 2022; Sun & Kim, 2022; Wang et al., 2024; Wang & El-Gohary, 2023a, 2023b; Zhong et al., 2020)
Building design analysis	25	(Beach et al., 2015; Bloch et al., 2023; Bloch & Sacks, 2020; Chen et al., 2020; Gao et al., 2022; Guo et al., 2021; Jiang et al., 2022; Li et al., 2016, 2024; Li et al., 2023; Malsane et al., 2015; Martins & Abrantes, 2010; Nawari, 2019; Peng & Liu, 2023; Schuk et al., 2022; Soliman-Junior et al., 2021; Sydora & Stroulia, 2020; Xue & Zhang, 2022; Yang et al., 2023; Zhang & El-Gohary, 2017a; Zhang & El-Gohary, 2021; Zheng et al., 2022; Zhong et al., 2012; Zhou et al., 2022, 2022)
Energy efficiency	2	(Zhou & El-Gohary, 2016, 2017)
Fire safety	4	(Ismail et al., 2023; Li et al., 2024; Solihin et al., 2020; Wang et al., 2023)

The systems were developed utilising advanced technologies such as artificial intelligence (machine learning, neural networks, and natural language processing), graph-based methods, semantic enrichment and representation, and general rule representation analysis (Table 7). However, it should be noted from the table that multiple papers can apply the same techniques, while a single paper can have multiple techniques.

Table. 7. ACC techniques in AEC (Source: Authors' findings).

Technique	No of studies	References
Artificial intelligence	19	(Guo et al., 2021; Ismail et al., 2023; Li et al., 2016, 2024; Macit İlal & Günaydın, 2017; Melzner et al., 2013; Nawari, 2019; Pan et al., 2022; Shen et al., 2022; Sun & Kim, 2022; Wang & El-Gohary, 2023a, 2023b; Wang et al., 2023, 2023; Zhang & El-Gohary, 2017a; Zhang & El-Gohary, 2021; Zheng et al., 2022; Zhong et al., 2020; Zhong et al., 2012; Zhou et al., 2022)
Graph-based methods	8	(Bloch et al., 2023; Chen et al., 2020; Li et al., 2024; Pan et al., 2022; Peng & Liu, 2023; Schuk et al., 2022; Wang & El-Gohary, 2023b; Yang et al., 2023)
Semantic and Ontology approaches	10	(Jiang et al., 2022; Ma et al., 2024; Malsane et al., 2015; Shen et al., 2022; Soliman-Junior et al., 2020; Zhang & El-Gohary, 2017a; Zheng et al., 2022; Zhong et al., 2012; Zhou & El-Gohary, 2016, 2017)
Rule-based approaches	9	(Beach et al., 2015; Eastman et al., 2009; Guo et al., 2021; Jiang et al., 2022; Jiang & Leicht, 2015; Shen et al., 2022; Solihin et al., 2020; Sydora & Stroulia, 2020; Xue & Zhang, 2022)
General rule representation analysis	3	(Beach et al., 2024; Nuyts et al., 2024; Soliman-Junior et al., 2021)

The common ACC tasks carried out include information extraction and information transformation (Table 8). These findings corroborate the outcomes of the bibliometric analysis. The major domains where automated compliance checking in the AEC industry has been used significantly are discussed in the following subsections. However, it should be noted from the table that multiple papers can apply the same tasks, while a single paper can apply multiple tasks as well.

Table. 8. ACC Tasks in AEC (Source: Authors' findings).

Tasks	No of studies	References
Code compliance and error checking	12	(Beach et al., 2015; Gao et al., 2022; Li et al., 2024; Li et al., 2023; Macit İlal & Günaydın, 2017; Shen et al., 2022; Soliman-Junior et al., 2020; Sun & Kim, 2022; Yang et al., 2023; Zhou & El-Gohary, 2016, 2017; Zhou et al., 2022)
Information extraction and representation	20	(Beach et al., 2024; Bloch et al., 2023; Bloch & Sacks, 2020; Chen et al., 2020; Guo et al., 2021;

		Ismail et al., 2023; Martins & Abrantes, 2010; Melzner et al., 2013; Nawari, 2019; Nuyts et al., 2024; Pan et al., 2022; Peng & Liu, 2023; Wang & El-Gohary, 2023a, 2023b; Wang et al., 2023; Zhang & El-Gohary, 2017a; Zhang & El-Gohary, 2021; Zhou & El-Gohary, 2016, 2017; Zhou et al., 2022)
Rule interpretation	11	(Bloch & Sacks, 2020; Jiang et al., 2022; Li et al., 2016; Li et al., 2023; Malsane et al., 2015; Schuk et al., 2022; Xue & Zhang, 2022; Yang et al., 2023; Zhong et al., 2012)

Construction safety

Applications

The implementation of ACC has gained significant traction within the construction safety sector, primarily due to its imperative to process and analyse large volumes of data more efficiently than manual methods, improve adherence to safety regulations and mitigate accidents on construction sites (Zhang & El-Gohary, 2015). To this end, several solutions have been provided within the domain of construction safety using ACC. Melzner et al. (2013) developed a customisable safety rule-checking platform to visualise the fall protection equipment in BIM. The system can automatically generate take-off quantities and schedule information for installing and removing guardrails and hole covers for fall protection on construction sites. Other studies have developed solutions to assist in improving fall protection by analysing safety standards relating to falls on sites (Wang & El-Gohary, 2023a, 2023b). Researchers have also used ACC approach to identify accident causes and injury types in construction by integrating safety rules and reports (Pan et al., 2022; Shen et al., 2022), as well as to enhance the accuracy and performance of construction safety solutions using various technologies (Beach et al., 2020). These applications were achieved through the use of different technologies. This stresses the potential of ACC systems in enhancing safety and accidents prevention on construction sites, thus, improving overall safety management within construction environments. The application of ACC in this domain also reduces the potential for human error in the enforcement of safety protocols.

Technologies

Key technologies, including deep learning, NLP, and knowledge graphs, are instrumental in facilitating this trend. These sophisticated methodologies enable precise identification of safety requirements and potential infractions, thereby fostering proactive construction safety management. Ontology-driven approaches and semantic models further enable dynamic verification of safety rules and risk mitigation in construction endeavours (Shen et al., 2022). Graph-based technologies have also been integrated with ACC solutions in reporting and representing safety issues (Pan et al., 2022; Wang & El-Gohary, 2023b). On the other hand, machine learning and deep learning technologies have been applied to improve the performance of ACC solutions. For example, Bloch et al. (2023) developed a graph neural network based on ML for compliance checking in the safety domain. By integrating these technologies, safety management systems can autonomously interpret and enforce complex safety regulations, thereby minimising the potential for human error and enhancing overall safety on construction sites. The extensive integration of ACC in construction safety underscores its vital importance in upholding regulatory compliance and safeguarding workers and assets in construction environments. Thereby, improving safety outcomes and reducing risks on construction sites.

Tasks

Key activities within ACC include the extraction and transformation of safety regulations from textual sources, facilitating efficient interpretation and compliance with regulations. Researchers have successfully integrated solutions for classifying and transforming information for ACC in the safety management domain (Pan et al., 2022). In a similar vein, Wang & El-Gohary (2023a, 2023b) developed a procedure for extracting and reporting safety-related information. Other efforts have demonstrated the possibility of analysing regulatory documents to check for compliance with rules (Melzner et al., 2013; Soliman-Junior et al., 2020). By converting unstructured text into actionable insights, these systems effectively reduce risks and improve safety practices, ultimately leading to better project outcomes and regulatory compliance.

Building design analysis

Applications

ACC in building design encompasses specific applications, including ventilation, space/headroom requirements, energy performance assessments and underground garage designs. A framework for the automatic compliance checking system with BIM as the test target has been proposed (Chen et al., 2020). Additionally, Nawari (2019) created a Generalised Adaptive Framework (GAF) that supports a neutral data standard and lessens the limitations of the various design review process methods. Similarly, Zhou et al. (2022) created a semantic framework based on NLP that applies rule-based automated compliance checking for BIM during the design phase. The findings of the study enhanced the Design for Safety (DFS) concept and integration of building design with computing technology using ontology and BIM. These findings buttress how building design can be analysed using ACC to detect errors and make improvements at an early stage. It ensures that designs capture the requirements to meet the necessary standards and provide the essential functionalities.

Technologies

Techniques that utilise computational geometric methods and semantic enrichment facilitate the automated compliance verification of underground garage designs within BIM environments (Gao et al., 2022). In terms of energy performance, automated systems leveraging text and information analytics enable the verification and documentation of compliance with energy regulations (Zhou & El-Gohary, 2017). Furthermore, frameworks that combine neural networks with knowledge graphs have been established for automated compliance verification, which aids in the identification of errors and the labelling of text within BIM (Li et al., 2024). Nawari (2019) also developed a framework by transforming codes using the Transformation Reasoning Algorithm (TRA) and a generalised adaptive framework (GAF). Moreover, specialised approaches, such as employing graph neural networks for accessibility evaluations and the Visual Code Checking Language (VCCL) for assessing existing ACC systems, illustrate the variety of methodologies being utilised in building design compliance (Bloch et al., 2023; Preidel & Borrmann, 2015). Zhou & El-Gohary (2016) implemented ML techniques for ontology-based multilabel text classification of construction regulatory documents. This methodology enables ACC systems to systematically categorise and evaluate a variety of design requirements, ensuring compliance with structural integrity, zoning laws, and aesthetic criteria.

Tasks

The application of ACC has incorporated advanced techniques for information extraction and transformation, thereby enhancing both regulatory compliance and design productivity. A notable example is the work of Xue & Zhang (2022), who developed expanded rulesets for the transformation of regulatory information to facilitate automated compliance checking of building codes. Their research illustrates how NLP can convert intricate regulatory texts into structured data, which aids in the verification of compliance within architectural design. Similarly, the work by Yang et al. (2023) extracts design-related information semi-automatically. By automating the processes of extraction and transformation of regulatory information, these systems significantly improve the accuracy and efficiency of adherence to building codes, thereby ensuring that designs fulfil safety, structural integrity, and environmental standards.

Energy efficiency

Applications

The building sector has been tagged as responsible for about 40% of greenhouse gas emissions globally (Ürge-Vorsatz et al., 2020). Energy conservation has been a major discussion among industry practitioners, researchers, and policymakers over the past decade and beyond (Satola et al., 2022). The adoption of ACC has gained momentum in the field of energy efficiency in building design, primarily due to the necessity of adhering to rigorous energy performance standards and regulatory frameworks. For instance, Zhou & El-Gohary (2016, 2017) have created systems that employ text and information analytics for comprehensive automated energy code verification, which enhances the classification, extraction, and alignment of semantic data pertinent to energy performance. These systems streamline compliance checking and reporting and also significantly diminish manual labour while enhancing accuracy in fulfilling energy efficiency requirements.

Technologies

A pivotal technology contributing to progress in this domain is neural networks, which empower ACC systems to process extensive datasets and discern patterns associated with energy usage and efficiency. Ontology-based methodologies have been employed to improve the semantic understanding and representation of building energy codes within ACC systems. Zhou & El-Gohary (2016, 2017) implemented ontology-based techniques for improving the performance of building energy conservation. By organising energy regulations into ontological structures, ACC systems can automate the interpretation of intricate energy efficiency rules and stipulations. This strategy enhances the efficiency of compliance assessments by facilitating systematic comparisons between building energy models and regulatory standards.

Tasks

A prominent technology that has gained widespread application is natural language processing (NLP), which aids in the extraction of energy-related mandates and regulations from textual sources. For example, the studies by Zhou & El-Gohary (2016, 2017) can extract and categorise environmental regulatory requirements, thereby promoting automated compliance verification in energy efficiency. By converting regulatory information into structured formats, these systems optimise the verification process, ensuring that buildings satisfy rigorous energy efficiency standards.

Fire safety

Applications

The field of fire safety has witnessed considerable advancements in ACC, underscoring an increasing commitment to ensuring that buildings conform to rigorous fire safety standards. Ismail et al. (2023) introduced a user-centric, BIM-based ACC system designed specifically for Malaysian fire safety regulations. This innovative system employs NLP to facilitate automatic compliance verification, thereby ensuring that fire safety protocols are properly integrated into building designs with minimal manual oversight. In a similar vein, Wang et al. (2023) merged NLP with spatial geometric analysis to evaluate adherence to fire codes, concentrating on the spatial interrelations of building elements to guarantee the implementation of appropriate fire safety measures. The studies illustrate how ACC systems can effectively ensure compliance with fire safety mandates. This essentially aids in reducing the damages and losses as a result of fire.

Technologies

Ismail et al. (2023) employed a BIM-based approach for ACC in fire safety. Moreover, knowledge graph technologies have significantly contributed to the enhancement of semantic representation and analysis of fire safety regulations within the ACC system as illustrated by Li et al. (2024). The studies by Ismail et al. (2023) and Li et al. (2024) also integrated the ACC systems with neural network technologies. By organising fire safety regulations and their interrelations in a graphical format, knowledge graphs empower ACC systems to conduct thorough compliance evaluations across various building components and systems. This methodology not only improves the precision of fire safety assessments but also facilitates real-time updates and monitoring of regulatory modifications, ensuring ongoing compliance throughout the lifecycle of buildings.

Tasks

In the field of fire safety, the automation of compliance checking has increasingly depended on sophisticated information extraction and transformation methodologies to improve both the efficiency and precision of regulatory compliance. The study by Ismail et al. (2023) emphasises semantic enrichment to guarantee that buildings meet rigorous fire safety standards. Furthermore, the system developed by Li et al. (2024) organises regulatory information into ontological structures, to effectively identify and address fire safety risks. The studies facilitate the extraction and categorisation of safety requirements from intricate regulatory texts.

Challenges

Although ACC presents a range of advantages, it is simultaneously being hampered by various challenges within the AEC domain. These challenges prevent the effective running of the ACC systems, which can ultimately result in poor performance of the ACC systems. The various challenges are discussed as follows.

Handling complex and ambiguous regulations

A significant challenge lies in the intricate and fluctuating nature of regulatory standards, variations in design codes or regulatory standards based on geographical location, the type of project, and temporal changes. This inconsistency creates difficulties for automated systems, which must proficiently interpret and apply a wide array of regulatory texts to ensure adherence. For instance, the research conducted by Zhang & El-Gohary (2016) underscored parsing and comprehending complex legal terminology across different domains to be one of the challenges with ACC. This is further stressed by several studies that noted that complex terminologies result in ambiguities, which affect the accuracy of ACC systems (Soliman-Junior et al., 2021; Yamusa et al., 2024b; Zhang et al., 2023). Additionally, Ismail et al. (2023) identified the primary obstacle as being the difficulty of incorporating different fire guidelines on the same system, as well as the domain's restriction to a single BIM model. The interpretation of complex regulatory language and contextual stipulations can pose difficulties for ACC systems, which often depend on established rules or patterns that may not comprehensively address all possible scenarios.

User interface and usability

ACC tools often have complex interfaces that may not be user-friendly for all stakeholders. This is because ACC tools are usually developed by integrating various techniques together. Ensuring that tools are accessible and intuitive for users with varying levels of technical expertise remains a challenge (Ismail et al., 2023). The need for customisation to fit specific projects or regulatory requirements can be a barrier. Developing tools that are flexible yet easy to configure for different contexts is an ongoing challenge (Lee et al., 2019).

Semantic and ontological limitations

Another major challenge involves the integration and interoperability of diverse data sources and systems. Numerous ACC systems depend on the amalgamation of data from various origins, including BIM, regulatory databases, and sensor data. Achieving seamless integration and ensuring data interoperability are essential for these systems to accurately evaluate compliance. Developing comprehensive and adaptable semantic models for compliance checking is challenging. Current systems may struggle with representing the full scope of regulations or adapting to new requirements (Li et al., 2023). Creating and maintaining ontologies that accurately reflect regulatory requirements is complex. Ontologies need to be sufficiently detailed and flexible to handle diverse and evolving regulations, which can be challenging (Guo et al., 2021).

Scalability and adaptability issues

Furthermore, the scalability and adaptability of ACC systems pose considerable challenges. As the scope of projects and regulatory demands change, these systems must be capable of scaling to manage substantial data volumes and adapting to incorporate new regulations and technologies. In their study, Li et al. (2024) identified the need to improve the scalability and adaptability of the ACC systems. Integrating automated compliance checking tools with existing design and construction workflows can be problematic. The challenge lies in ensuring seamless interaction between new tools and established systems, which often requires substantial customisation (Jiang et al., 2022). Automated systems need to adapt quickly to changes in regulations. Maintaining up-to-date compliance checking tools amidst evolving regulatory landscapes is a significant challenge (Zhang & El-Gohary, 2016).

Accuracy and reliability of automated tools

The challenge of ensuring the accuracy and reliability of ACC systems persists as a significant concern. It is imperative for systems to accurately discern and interpret complex requirements to avert mistakes that may jeopardize safety or legal adherence. The limitation of ML in ACC systems, which prevents it from reasoning with rules that call for human judgment, is another significant obstacle (Zhang et al., 2022). This is exemplified by the work of (Yamusa et al., 2024c), who stressed the need to improve the accuracy of ML-based ACC systems. Similar challenges were also noted by (Sun & Kim, 2022), who posited that for BIM object recognition, judgments could only be made based on the AI-recognised space-object relationship and that only properties that could be visualised were taken into account. It's still difficult for rule writers or designers to easily impose constraints (Nuyts et al., 2024). This can be achieved by developing datasets specifically for training ACC systems.

Data quality and consistency

Another major challenge is the subjectivity of the ACC process which makes the automation of the ACC system more difficult. Similarly, the poor performance of the ML models in addressing subjective rules is an issue to deal with. The results provide probabilistic outcomes, thus making the systems less reliable. The use of just the basic part of the NLP method is also proving to be a challenge (Zhou et al., 2022). Although efforts have been directed at reducing the issue of subjectivity (Wang & El-Gohary, 2023a; Zhang et al., 2023), there is still a need for training datasets, and developing models specifically addressing subjective requirements in ACC. ACC systems are highly dependent on the quality of input data. Inaccurate or incomplete data can lead to incorrect compliance results, highlighting the need for robust data management practices (Nuyts et al., 2024). Ensuring consistency in data interpretation and compliance results across different systems and tools is challenging. Inconsistent results can undermine the reliability of ACC (Bloch et al., 2023).

Resource and cost constraints

The issue of integrating ACC into building regulations still relies greatly on human labour for the present rule-development process (Yamusa et al., 2024c). This can result in some inefficiencies of the traditional compliance checking approach including errors, and time consuming. Developing advanced ACC systems, however, can be costly. The need for specialised expertise, extensive testing, and integration with existing systems can drive up costs (Zhang et al., 2023). Allocating sufficient resources for ongoing maintenance, updates, and user support is essential but can be challenging, especially for smaller organisations or projects (Zhang & El-Gohary, 2021).

The current status of research in ACC showing application domains, techniques, and tasks linked with the various challenges and opportunities are summarised in Figure 7.

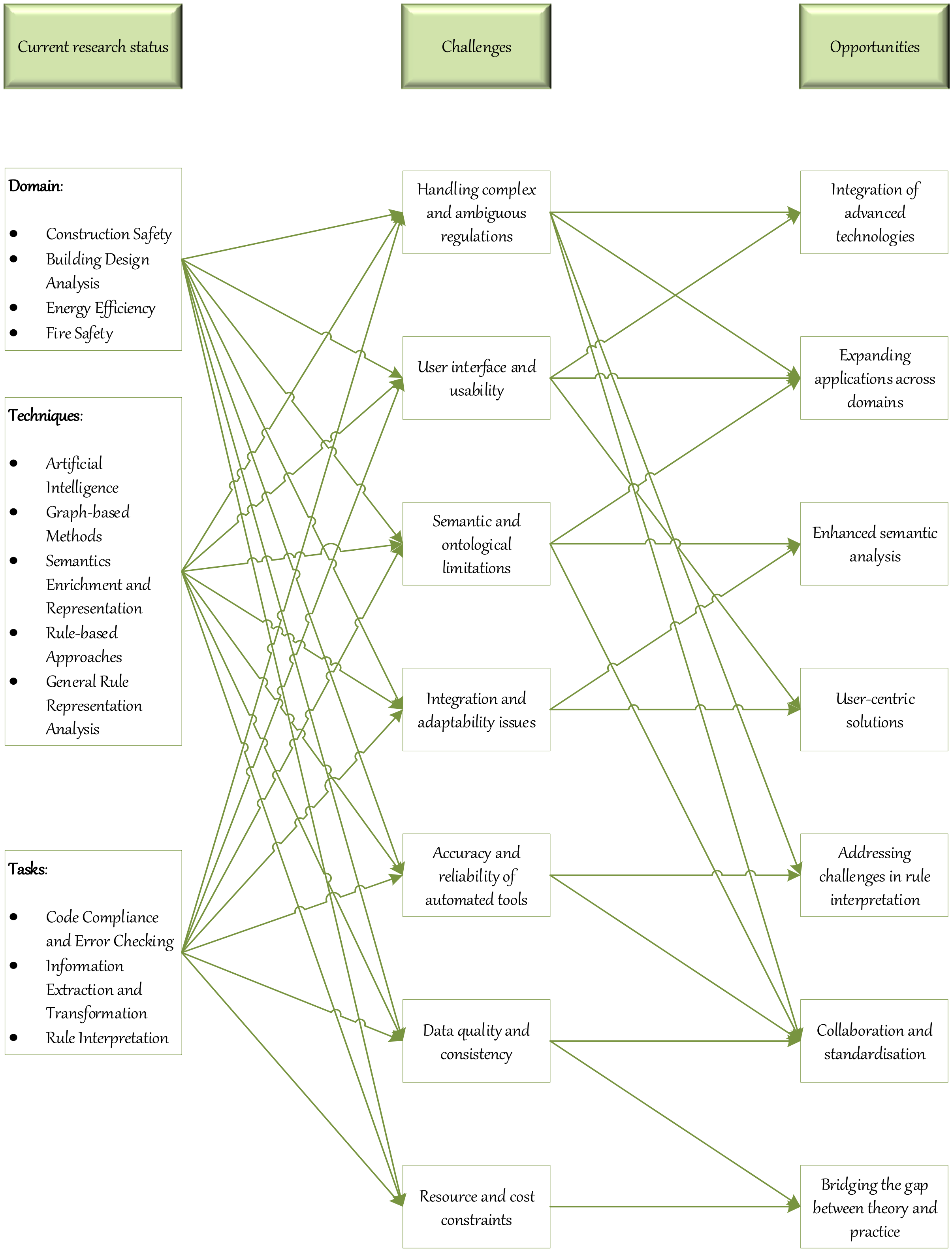

Fig. 7. Research framework showing the links between the mainstream current state, challenges and opportunities.

Opportunities

Integration of advanced technologies

Numerous research efforts employ neural networks, alongside various machine learning methodologies for applications including named entity recognition, information extraction, and compliance checking. There exists an opportunity to enhance these approaches by merging them with additional artificial intelligence technologies or by augmenting their training datasets, thereby increasing both accuracy and robustness. NLP is commonly applied to extract and interpret regulatory information. Progress in NLP could facilitate more precise parsing of intricate regulatory language and improve the management of context-specific subtleties. The application of knowledge graphs to organise and interrelate data can significantly advance the automated comprehension of building codes and regulations. Broadening the scope of these graphs to encompass a wider array of complex regulations may further strengthen compliance verification capabilities. This will improve the robustness of ACC systems, given their potential to surpass the human technique in accuracy, rapidness, and reliability (Wang & El-Gohary, 2023a).

Enhanced semantic analysis

Studies indicate an increasing focus on semantic enrichment as a means to enhance compliance verification processes. There is potential for the advancement of more intricate semantic models capable of addressing the varied and changing landscape of building regulations. Approaches grounded in ontology are employed for the interpretation of rules and the assessment of compliance. There are opportunities to develop more extensive and flexible ontologies that can be modified in real-time as regulations progress. This can help achieve the incorporation of ACC across more BIM platforms and building requirements (Ismail et al., 2023).

Expanding applications across domains

Tools designed for ACC, particularly in domains like building retrofitting, demolition and waste control, are relatively scarce. Owing to the potential of ACC, it can ensure that these activities are conducted safely, and in line with regulations. This is owing to calls for enhanced construction processes like the UK Government's Sustainable Construction Strategy published in 2008 supported by the Site Waste Management Plans Regulation (2008) to facilitate waste management in construction. Given the special regulations guiding areas like waste management and demolition, there exists an opportunity to create specialised tools that address this critical domain, thereby ensuring adherence to regulations. Additionally, the automation of compliance checking for energy codes is becoming increasingly significant. Future investigations could aim to merge energy performance metrics with compliance frameworks to promote sustainable construction practices.

User-centric solutions

Numerous research efforts highlight the importance of implementing user-friendly methods for compliance checking. The creation of intuitive and easily navigable tools can promote acceptance and usability among practitioners possessing diverse degrees of technical knowledge. This will help in easing and managing the constraints by regulation designers (Nuyts et al., 2024). Providing adaptable solutions that can be modified to meet specific project needs or regulatory frameworks can significantly improve the efficacy and efficiency of compliance checking processes.

Bridging the gap between theory and practice

A variety of tools and methodologies require empirical validation through real-world case studies. For example, (Zhang et al., 2023) established a sound taxonomy of ambiguities in ACC for Health Buildings, which is still theoretical. (Yamusa, et al., 2024b) also established a taxonomy of ambiguities in ACC for green buildings. Some of these efforts on ACC are halfway, and not implement for use in practice. Broadening research efforts to encompass additional case studies and practical implementations can yield valuable insights regarding the efficacy of various strategies and highlight potential areas for enhancement. Furthermore, ensuring that ACC tools are fully compatible with current building design and management processes can significantly improve their practicality and likelihood of adoption.

Addressing challenges in rule interpretation

Tackling the difficulties associated with the interpretation of intricate and ambiguous regulations through the utilisation of advanced artificial intelligence and semantic analysis has the potential to enhance the precision and reliability of ACC. The creation of systems capable of adjusting to regulatory changes without necessitating significant reprogramming or manual interventions can ensure that compliance tools remain pertinent and efficient. This serves to ameliorate the human involvement that rule interpretation (Jiang et al., 2022) and reducing clause complexities (Li et al., 2016), thereby improving the efficiency of rule interpretation.

Collaboration and standardisation

The collaboration among researchers, industry experts, and regulatory agencies can facilitate the establishment of standardised methodologies and instruments that serve the interests of the entire sector. The formulation of standards for automated compliance checking tools is essential for achieving uniformity and dependability across various systems and applications. With BIM becoming the standard in AEC in many countries like the UK, and its potential to provide good results, it provides the avenue for seamless interface with ACC systems (Eastman et al., 2009; Ismail et al., 2023). Additionally, research indicates that the capabilities of ACC systems can be more extensively applied across diverse construction sectors.

CONCLUSION

This research presents a thorough examination of the present status of ACC within the AEC sector, emphasising its application areas, techniques applied as well as opportunities and challenges. Utilising a detailed bibliometric analysis of literature obtained from the Scopus database, the study uncovers critical trends and patterns that illustrate the development and influence of ACC systems. The study employed in-depth analysis to determine the application areas, techniques applied, as well as the opportunities and challenges of ACC within the AEC sector. The bibliometric review findings show a significant rise in ACC publications from 2003 onwards, reflecting growing interest and advancements in this field. The findings also show that China, US, South Korea, Australia and India are the leading countries in ACC research. For authors, El-Gohary, N., Zhang, R., Zhou, P., Zhang, J., and Zhong, B. were found to be the leading researchers in the ACC domain. Automation in Construction, Journal of Computing in Civil Engineering, Advanced Engineering Informatics, Applied Sciences, and Sensors were found to be the leading journals in ACC research. Finally, Neural networks, feature extraction, NLP, information extraction, and machine learning are the top five author keywords.

The principal outcomes of this in-depth review indicate that ACC systems have been significantly applied to address issues in the areas of construction safety, building design, energy efficiency and fire safety. The review also found out the different technologies used in ACC systems development including artificial intelligence, specifically machine learning, neural networks, and natural language processing; graph-based methods; semantic enrichment and representation; and general rule representation analysis. The study also found that ACC can significantly improve operational efficiency while minimising human error in compliance checking processes. The study uncovered ACC application challenges including technological limitations and integration issues. Furthermore, the research highlights the capability of ACC systems to efficiently and accurately handle large datasets, thereby ensuring compliance with regulatory requirements through integration with enhanced technologies, expanding application domains, collaborations and standardisations.

This study theoretically enriches the academic conversation surrounding ACC by delivering a comprehensive evaluation of its applications and developments. It presents an in-depth analysis of the trends and patterns prevalent in ACC research, thereby paving the way for subsequent investigations in this field. From a practical standpoint, the results emphasise the critical role of ACC systems in enhancing project performance, minimising expenses, and fostering collaboration among stakeholders within the AEC sector. Furthermore, the research illustrates the potential for integrating ACC systems with BIM platforms, which could significantly optimise compliance checking processes.

In order to enhance the integration and efficacy of ACC systems within the AEC sector, this study recommends promoting ACC systems that can seamlessly interface with BIM platforms. This integration is essential for ensuring thorough compliance verification throughout the project lifecycle. Additionally, the implementation of training initiatives aimed at increasing stakeholder awareness and proficiency in utilising ACC systems is crucial for fostering effective adoption and use. Furthermore, there is a need to investigate the potential of merging automated and semi-automated methodologies to tackle intricate compliance verification tasks that may necessitate human judgment.

To maximise the advantages of ACC within the AEC industry, subsequent research should focus on the application of advanced algorithms and machine learning methodologies to improve the precision and reliability of ACC systems. Research efforts should also aim to develop methods for the intelligent identification and representation of quantitative attributes that are challenging to visualise, thereby enhancing the overall effectiveness of ACC systems. Lastly, investigations should assess the applicability of ACC systems across various construction sectors, including infrastructure and industrial projects, to expand their influence and utility.

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ACKNOWLEDGMENTS

This paper is part of a larger research project funded by Innovate UK (Project ID: P33796). The project involves the development of an advanced AI-based Intelligent Golden Thread System for Building Safety Management (i-GBSM). Papers may be published in other sources which MAY share similar background. However, the works will have different scopes, objectives, and findings.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work.

FIGURES

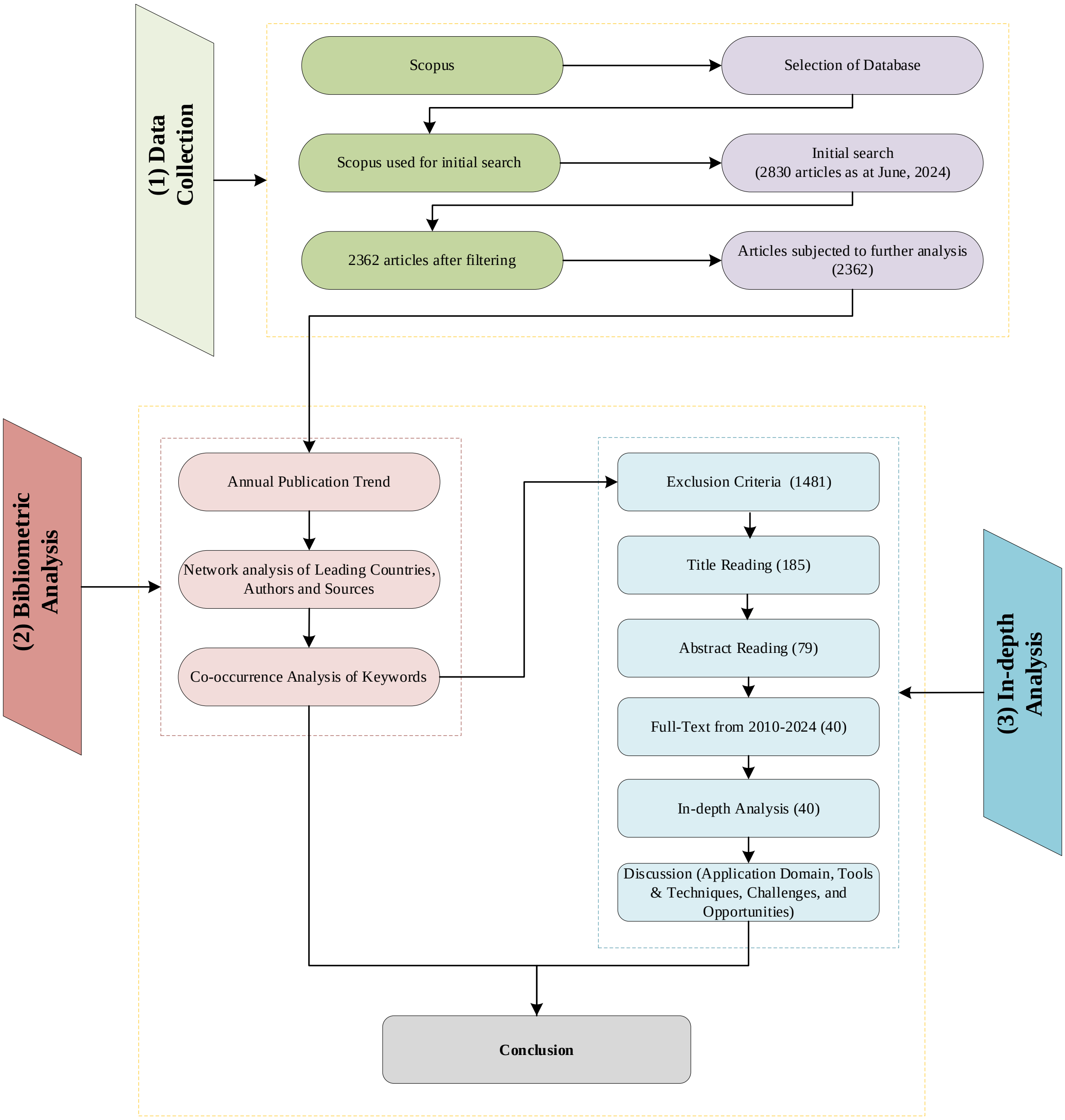

Fig. 1. Research methodology (Source: Authors).

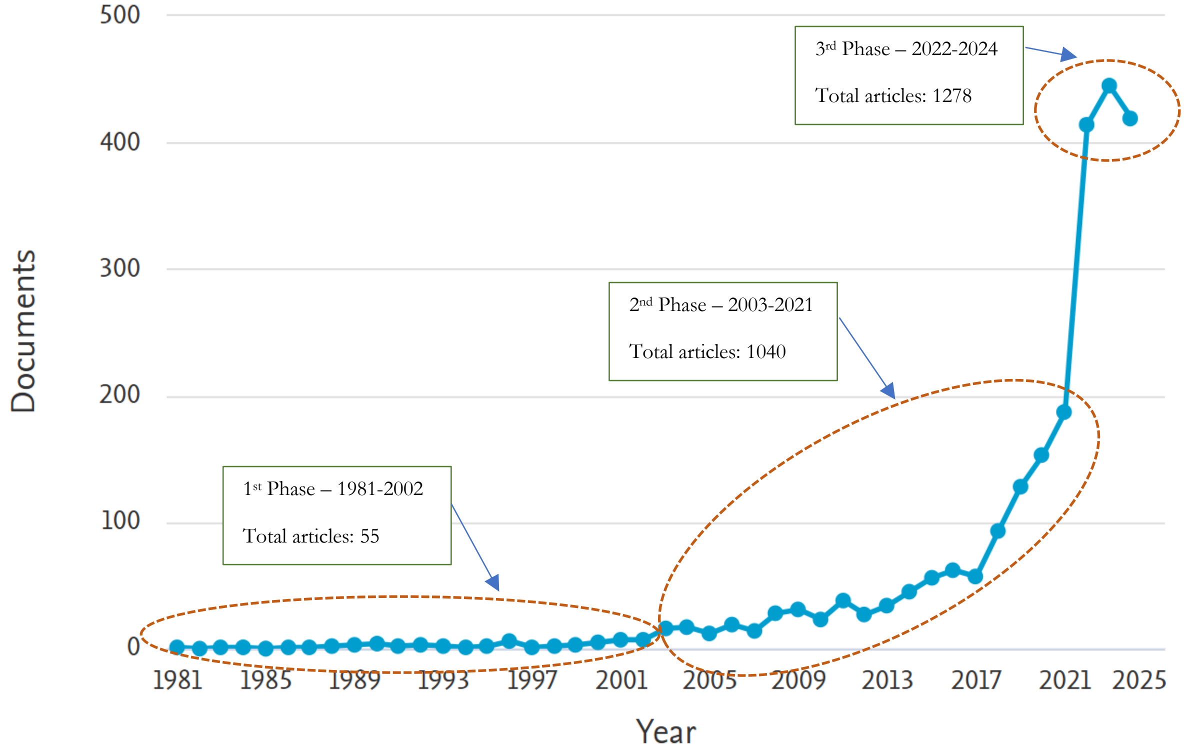

Fig. 2. Annual publication trend of ACC application in AEC (as of June 2024) (Source: Authors).

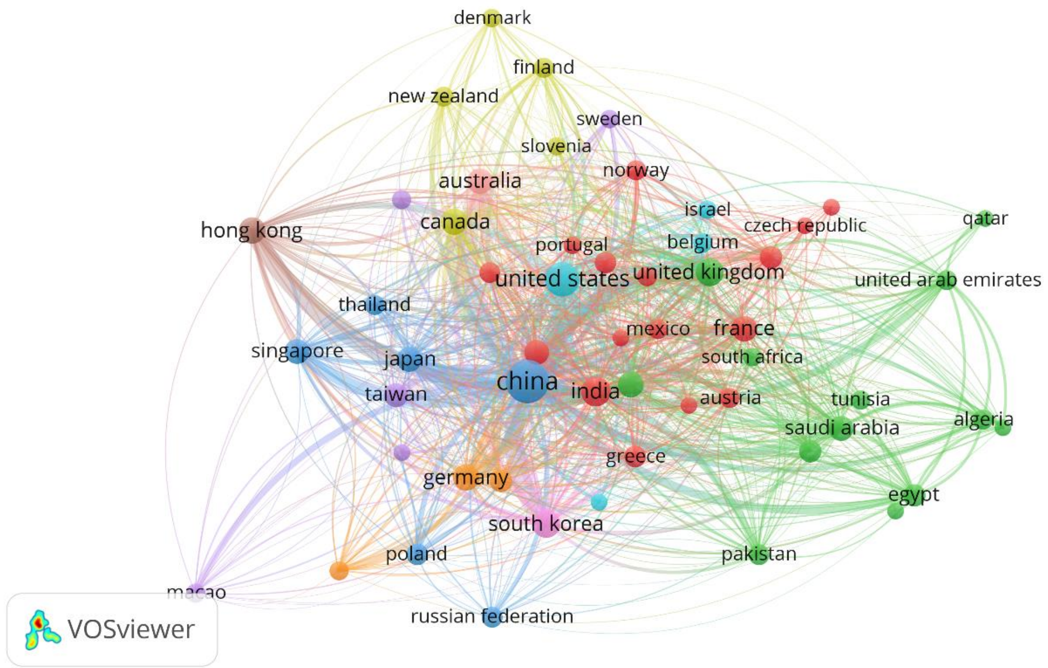

Fig. 3. Visualisation for major contributing countries in ACC research (Source: Authors).

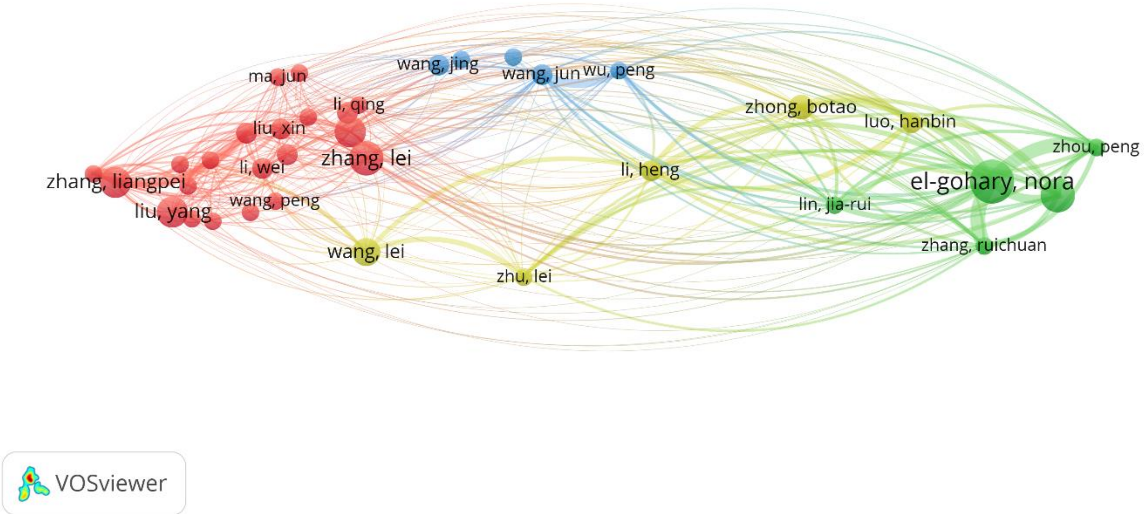

Fig. 4. Visualisation for leading authors in ACC research (Source: Authors).

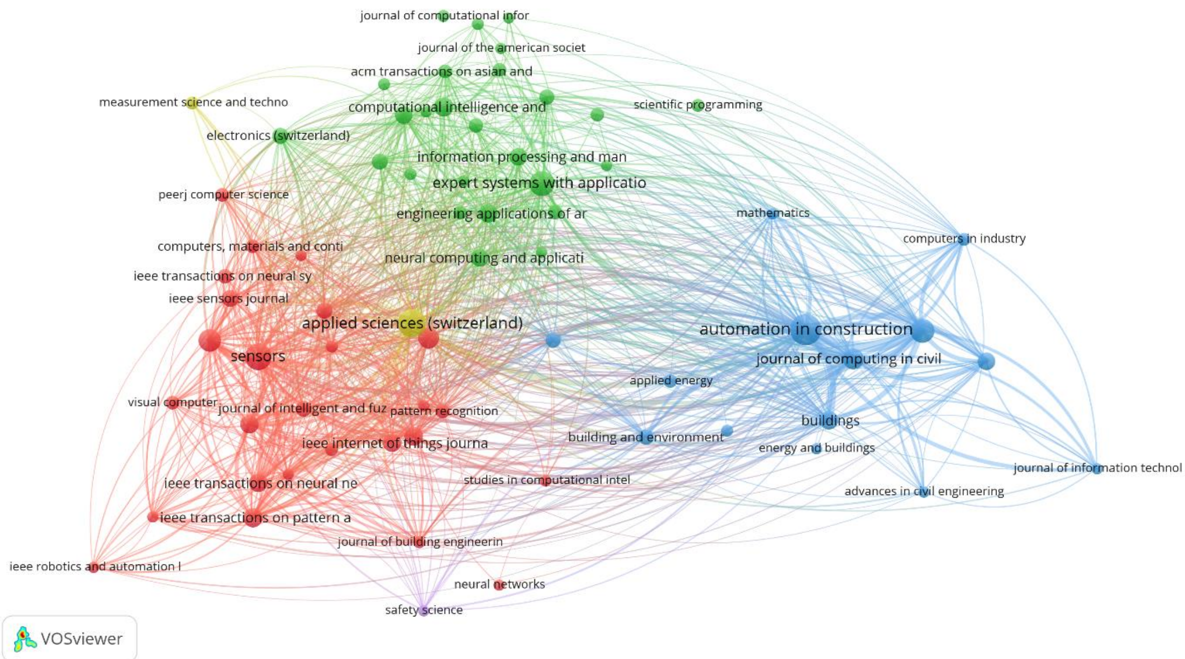

Fig. 5. Visualisation for leading research sources in ACC research (Source: Authors).

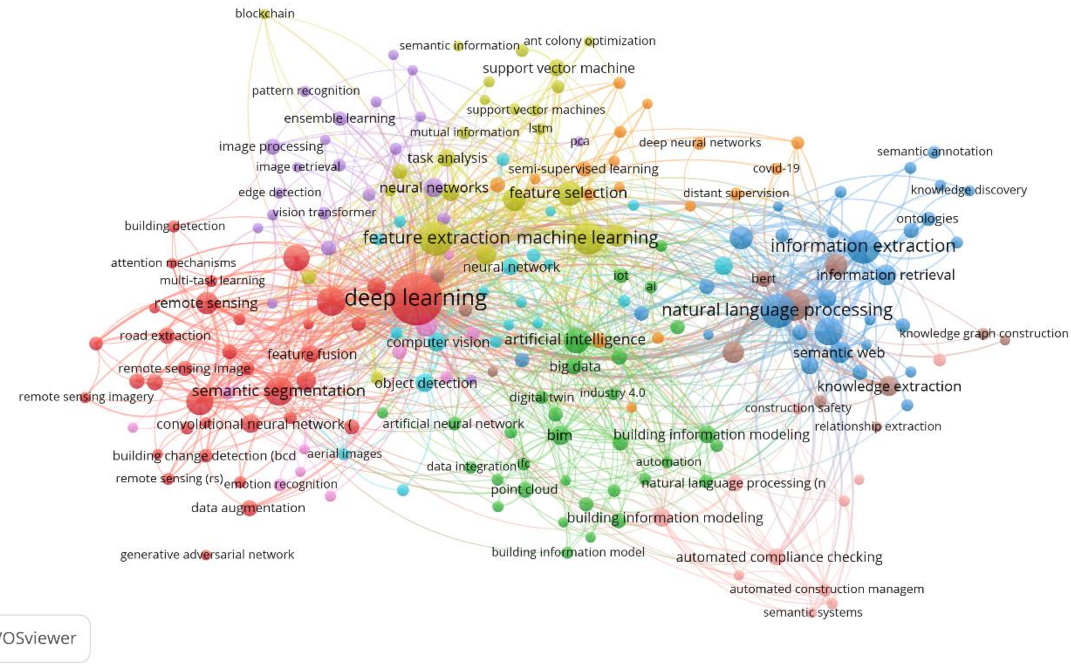

Fig. 6. Keyword co-occurrence network for ACC research (Source: Authors).

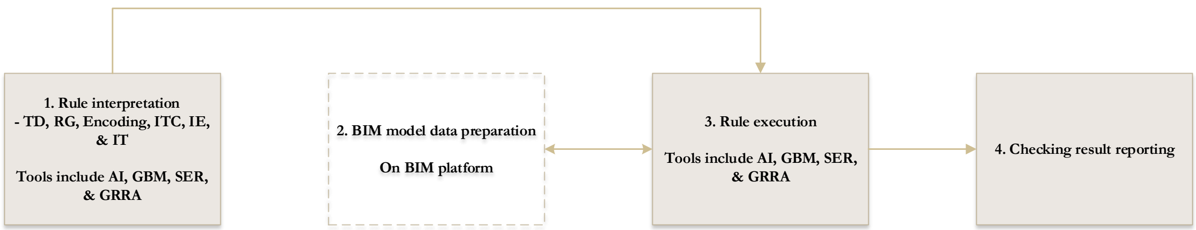

Fig. 7. General ACC process (Source: Authors).
*TD – Taxonomy development; RD – Rules generation; ITC – Information text classification; IE – Information extraction; IT – Information
**AI - Artificial intelligence; GRM – Graph-based method; SER – Semantic enrichment & representation; GRRA – General rule representation analysis

FIGURE CAPTIONS

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