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Review

Extended reality in AEC

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ABSTRACT

This article presents a survey on extended reality (XR) application to architecture, engineering, and construction (AEC). A systematic literature review (SLR) of studies found in the Scopus digital library is carried out for that purpose. The SLR comprises 983 relevant papers published between 2011 and 2022. It frames and aggregates research by the AEC field and by the usage of XR technologies. With that aim, specific taxonomies are developed and applied. Research typologies, including used approaches and contributions, are also examined. Furthermore, the limitations and challenges cited in the analyzed studies are addressed. This SLR is primarily addressed to researchers for decision-making in identifying and scoping future research activities. It is also directed to AEC practitioners as a source to determine the conditions in which XR can be used and what its implications are.

1. Introduction

This article examines the most recent research on extended reality (XR) applied to the architecture, engineering, and construction (AEC) area and analyzes its progression throughout more than one decade. The analysis is carried out through a systematic literature review (SLR), which includes 983 relevant papers published between 2011 and 2022. These studies were found using the Scopus digital library[2]. The SLR is addressed to researchers for identifying and scoping future research activities. It is also directed at AEC practitioners as a source to distinguish between commonly held beliefs and reality. In that scope, it serves as a source of information for decision-making, as it helps identify the conditions in which XR can be used and what its implications are.

In order to attend to the research questions, this work followed an unbiased search strategy for finding primary studies. These are existing individual studies gathered using the search strategy mentioned above. In addition, a search for secondary studies was carried out with the objective of discovering related work. These studies consist of the systematization of data previously gathered from a set of selected relevant primary studies [1].

A dedicated review protocol was developed with the objective of systematizing the literature review. This protocol defines a group of research questions that reflect the fundamental goals of the SLR. It includes a set of selection criteria aimed at filtering primary studies based on their relevance to the research questions. It also contemplates procedures for extracting data from the selected studies. Such procedures define the way that studies are classified. This classification uses a series of taxonomies and other classification methodologies that frame each study in specific categories.

The categorization covers aspects such as the research approach associated with the primary studies. It also includes the contributions of studies and the AEC fields addressed. Likewise, XR aspects, like the type of reality that studies are focused on, the display, the kind of input, and the existence of feedback, are covered by specific classification. Furthermore, the studies are categorized by the type of benefits, limitations, and challenges cited.

In addition to the categorical data that results from framing studies in the defined classification methodologies, the analysis also synthesizes continuous data. Such data is generated by means of a quality instrument consisting of a checklist of quality factors. These factors allow the scoring of primary studies in terms of 'quality'. The subjectivity of this approach is discussed in Section 5.2.

In this introduction, relevant background concerning XR and AEC is addressed (Sections 1.1, 1.2, and 1.3).

In Section 2, related literature review work, in the scope of XR in AEC, is presented and discussed. Section 3 describes the review protocol and methodology used in this SLR. The results of the SLR are presented and discussed in the scope of the research questions in Section 4.

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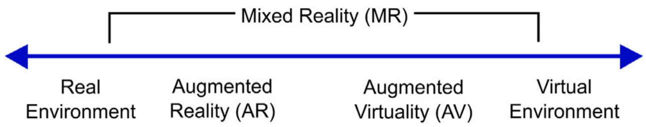

Fig. 1. Reality–virtuality continuum [2].

Finally, in Section 5, the conclusions of the work are presented, including the main contributions, research limitations, and a reflection regarding possible future directions.

1.1. Extended reality

XR refers to the set of real-and-virtual combined environments such as augmented reality (AR), mixed reality (MR), and virtual reality (VR). The XR spectrum has been conceptualized by Milgram [2] in the *reality–virtuality continuum*. This concept encompasses all possible variations of real and virtual objects (Fig. 1). While VR allows the user to submerge in immersive environments, AR enables the overlapping of relevant virtual elements to the observed reality. Other notable modalities of the XR spectrum include mixed reality (MR), augmented virtuality (AV) and diminished reality [3,4].

XR technologies have had considerable growth in popularity in recent years [5]. This growth has been in part due to the evolution of visualization and interaction techniques. But also because more capable software, application program interfaces, and tracking methods have been developed [6]. Furthermore, significant advances in the latest generations of dedicated XR hardware, like head-mounted displays (HMD), have been made. Such advances include increased definition and overall quality of cameras and sensors [7]. They also encompass a higher resolution of displays and a wider field of view. In that respect, the growth in speed and efficiency of graphical processors has been pivotal [8].

Component miniaturization has determined the emergence of entirely standalone devices that do not require XR devices to be connected to a PC.[3] Most modern XR controllers also include haptic feedback and some[4] HMDs can be used for both VR and AR. These technological developments have been accompanied by a decrease in the cost of hardware [9]. As a result, a wide range of industry areas have had the opportunity to apply XR to its processes. These include areas where the use of traditional visualization techniques has been long-established. The research work done in XR has supported this growing trend in the industry. Such research has shown that XR can bring tangible advantages in many areas, including in AEC [10].

1.2. Architecture, engineering, and construction

The term AEC encompasses three major areas within the construction industry: architecture, engineering, and construction. It concerns the provision of services within a construction project [11]. This provision presupposes the collaboration between the different players in the project. Such players may include *e.g.,* architects, civil engineers, or facility managers.[5]

The first element of AEC is architecture, which is traditionally defined as the art and practice of the design of buildings [12]. However, other disciplines can be included in the architecture area, such as urban planning [13], landscape design, interior architecture [14], and the architectural restoration of buildings and other structures.

The second element of AEC, engineering, refers to the classes of engineering directly related to the construction industry. These include such fields as civil engineering, generally responsible for the design and construction of public works [15], and structural engineering, responsible for the conception and design of structures [16]. The engineering area also encompasses geotechnical engineering (which deals with soils and rock structures) [17], transportation engineering (the analysis of motor traffic and design of roads and railways) [18], and hydraulic engineering (the analysis and design of *e.g.,* pipe networks, channels, and other water-related structures) [19]. Furthermore, it comprises construction engineering (which manages the constructive aspects of buildings and other structures) [20], municipal engineering (focused on municipal public works, *e.g.,* sewer systems and waterworks) [21], and environmental engineering (which deals with environmental issues in construction projects) [22]. In this SLR, facility management (the management of the operational aspects of buildings and infrastructures) [23] was also included in the engineering area.

Finally, the third element, construction, encompasses all the activities related to the execution of the built environment. Such activities include *e.g.,* steelworks, masonry, roofing, or concreting, among many others, as illustrated in Fig. 4. Management activities, such as construction management (the management of the construction job site) [24], which is closely related to construction engineering, and safety management (that deals with the prevention of accidents and injuries in the construction job site) [25] were also considered. Furthermore, support activities for the execution itself were taken into account. Such activities include surveying and marketing construction projects.

1.3. XR in AEC

The AEC area has been on the front line regarding the early adoption of technological innovations. With the advent of the fourth industrial revolution, AEC has responded with Construction 4.0 [26]. This concept includes, among others, the integration of the physical and the virtual in the construction activity. Its primary purpose is to unlock the construction industry digitalization potential [10], to improve the sector's performance.

As such, the construction industry is investing in emerging technologies such as artificial intelligence and big data analytics. With building information modeling (BIM) [27] as a central point, it is also experimenting with advanced visualization technologies based on XR. The academic community has responded to that challenge with a reinforced research interest in XR applied to AEC. This trend has had a very significant increase over the last decade. In fact, the number of studies has skyrocketed since 2011, as will be discussed in Section 4.1.

2. Related work

This section addresses previous literature reviews in the scope of XR in AEC. The set of 36 secondary studies analyzed includes SLRs and other literature reviews. They are presented and discussed to assess the need for the current SLR. The reviews were published in the last decade, and their chronological distribution is represented in Fig. 2.

Regarding the review scope, multiple existing secondary studies focus either on a specific XR technology (*e.g.,* VR or AR), on a particular AEC field (*e.g.,* architectural design), or even on certain types of structures (*e.g.,* tunnels).

In what concerns research on specific XR technologies, Zhang et al. [28] identified research trends and opportunities in VR applications for the built environment. Their SLR included 229 journal articles and provided a quantitative analysis of the use of VR. Chen and Xue [29] addressed the use of AR in construction. They analyzed 69 studies to identify the benefits that AR systems can bring to the

[3] One example is the stand-alone AR/MR headset *Hololens 2* (https://www.microsoft.com/en-us/hololens/hardware).

[4] Such as the *Meta Quest Pro* (https://www.meta.com/es/quest/quest-pro/) or the *Apple Vision Pro* (https://www.apple.com/apple-vision-pro/) headsets.

[5] The acronym AEC is often extended to embrace other areas, *e.g.,* AECO or AEC/FM to encompass Operation or Facility Management, respectively. In this SLR, the term AEC is used with a broader meaning, including the services of professionals related to facility management, operations, and maintenance.

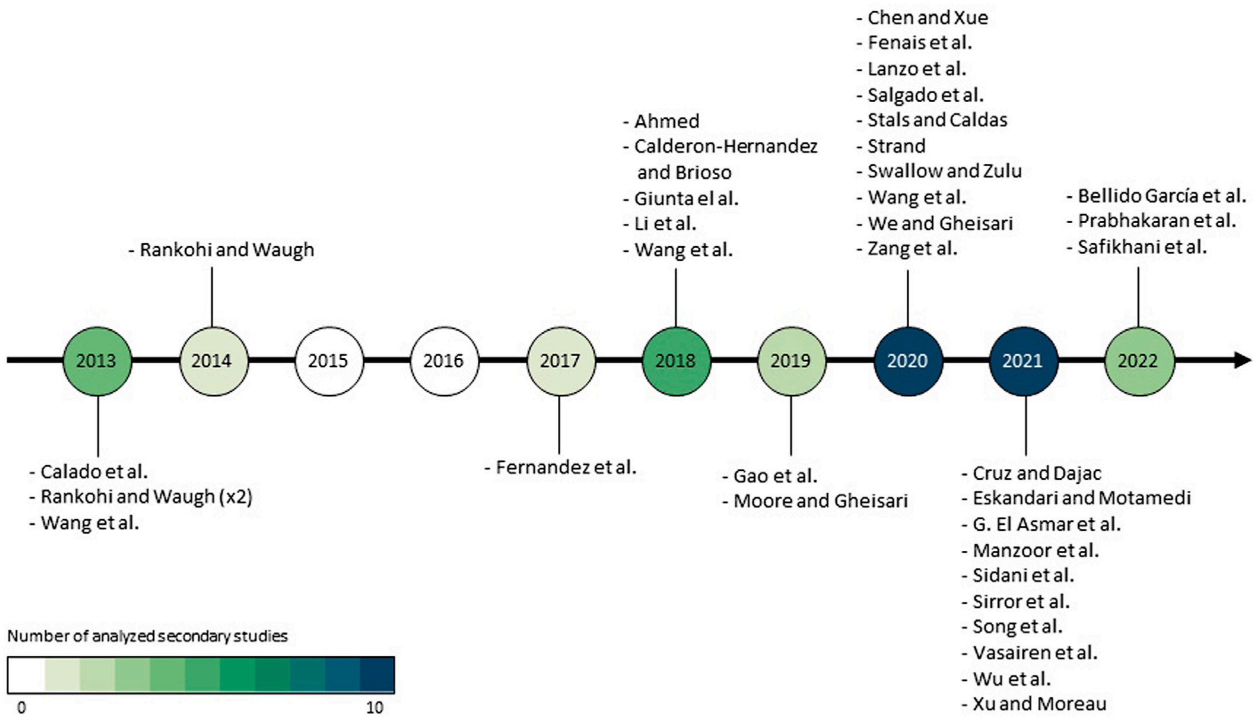

Fig. 2. Chronology of related work.

construction industry. Likewise, Xu et al. [30] carried out a literature review of AR applications in civil infrastructure. The review focused on research published between 2016 and 2020 and discussed challenges and future applications.

In what regards the research of XR in specific AEC fields, Ahmed [31] addressed the use of VR and AR in construction management. The literature review included 84 relevant papers published from 1997 to 2018. Gao et al. [32] created an SLR concerning the effectiveness of traditional tools and computer-aided technologies (including VR and AR) for health and safety training in construction. A total of 49 studies were analyzed. This broader scope review focused on effectiveness and classified studies by technology and training area. Stals and Caldas [33] focused on XR research in professional architecture practice. The SLR encompassed 201 studies published from 2015 to 2019. The authors pointed out that the existing XR tools were rarely developed with professional architects' real practices in mind.

There are also reviews concerning specific XR technologies in particular AEC fields, like the work by Swallow and Zulu [34], which made a scoping review [35] on the impact of VR on construction health and safety. They point out that most of the 24 studies analyzed focused on safety training, and very few addressed health and safety performance. Likewise, Calado et al. [36] carried out a brief literature review regarding the application of VR to study interaction in the built space.

Calderon-Hernandez and Brioso [37] developed a literature review regarding the joint use of BIM, AR, and Lean Construction [38] in the design and construction stages. The review used 116 papers published between 2014–2018. The authors pointed out that limited evidence was found that supports the effective integration of the addressed construction disciplines with AR. Wu et al. [39] carried out a literature review concerning the integrated application of AR and BIM. They analyzed 50 studies and classified them into four categories: task guidance and information retrieval, design review, planning and control, and employees upskilling [40]. Likewise, Sidani et al. [41] analyzed the use of BIM-based VR. They identified and reviewed 16 relevant studies and concluded that VR tools are becoming viable additions to BIM methodology.

As observed in the existing work presented above, there is still a lack of literature reviews that comprehensively encompass the wide range of AEC fields and XR technologies over a representative period. On the other hand, despite addressing them, some reviews cover too wide scopes without being dedicated explicitly to XR or AEC. Such an example is the work developed by Manzoor et al. [42], which created an SLR concerning the use of digital technologies in AEC. They qualitatively reviewed 200 studies and identified trends, patterns, and future directions. The review also encompassed a broad time frame (1975–2020). However, this work did not specifically focus on XR technologies but on general digital technologies. Likewise, Vasarainen et al. [43] carried out a literature review concerning XR in collaborative working life settings. Although it addressed XR in AEC, that was not its primary focus. The current SLR aims to go beyond the limitations of such reviews by presenting a holistic perspective on XR in AEC as a wide-ranging sector over more than a decade.

Transparent data extraction and synthesis methods are essential for enhancing the credibility and reliability of the review findings. The proper categorization of AEC fields is vital in that regard. Wang et al. [44] reviewed the adoption of digital technology in off-site construction. They classified studies by application area and pointed out each technology's potential and limitations. Safikhani et al. [45] focused on using VR in the AEC area, particularly on BIM. The review analyzed 73 studies published between 2016 and 2021. These studies were classified according to their application area and the technologies used. The authors concluded that VR could be beneficial, amongst others, as a visualization tool in the design stage of an AEC project. An SLR concerning the use of VR in construction engineering education and training was carried out by Wang et al. [46]. A total of 66 articles were reviewed and classified by technology and engineering application type.

The AEC taxonomy used in the current SLR shares some similarities with the previously described literature reviews, namely the work proposed by Rankohi and Waugh [47], Safikhani et al. [45], and Wang et al. [44]. However, unlike these, it uses a top-down approach with a clear and simple top-level organization and a wide range of disciplines and fields within the lower level. Its logical structure allows easy navigation and comprehension. Such an approach is adaptable and offers comprehensive coverage of the AEC industry.

The existing secondary studies also vary regarding the classification approach for XR technologies. Wang et al. [48] addressed AR in the built environment in a literature review encompassing 120 studies published between 2005 and 2011. The studies were classified according to the type of XR display, registration method, interaction devices, display, and trackers, among others. Salgado et al. [49] focused on applications of AR and VR in the construction industry. They classified the technological aspects of 62 studies using keyword frequency.

A review by Li et al. [50] tackled VR and AR in construction safety. They analyzed 90 papers published from 2000 to 2017. The papers were classified using specific taxonomies for the XR modality and VR/AR input/output devices. Moore and Gheisari [51] developed an SLR focused on VR and MR applications also in construction safety. They selected 46 studies and classified them by type of peripheral hardware and XR software. G.El Asmar et al. [52] analyzed 49 articles published between 2013 to 2020 and addressed AR technological aspects such as ease of implementation, the field of view, hardware and software performance, occlusion, and immersiveness.

Similarly to the previously described secondary studies, the current SLR XR taxonomy also uses the type of reality, display, and input type. However, it also addresses other aspects, like the feedback type covered in the primary studies.

Multiple studies systematize the benefits of XR in AEC applications. Lanzo et al. [53] conducted an SLR on the uses of VR in engineering education. The authors analyzed 17 studies published between 2015 and 2019. They concluded that using VR and traditional engineering education methods had cognitive, skill-based, and affective learning benefits. A scoping review by Bellido and García [54] addressed AR in Latin-American engineering education. It highlighted the key benefits of AR in engineering. The review analyzed and classified 36 studies based on the pedagogical perspective, usage, interaction, devices, and software, among other factors.

Sirror et al. [55] did a literature review of VR in architecture education. They framed 26 studies (published between 2000 to 2020) in four areas: design, construction, surveying, and structural analysis. The authors concluded that VR is an effective means to transfer architectural information to learners. Unlike the previous works, which are primarily aimed at education applications, the review by Fernandez et al. [56] addressed the drivers for the application of pervasive AR [57] in the construction industry. The study identified the reduction of errors and costs as the main benefit of using AR.

The classification methods of these works share some characteristics with the current SLR. Nevertheless, the benefits classification approach adopted in this SLR goes a step further by considering the interdisciplinary aspects of AEC.

Several secondary studies addressed and systematized the limitations and challenges of using AR in AEC. Giunta et al. [58] analyzed the role of AR in design practice. The authors considered 21 studies and concluded that AR technologies still need to improve in supporting some stages of the design process. This lack of AR solutions is especially notorious in the initial and latest stages of the design process. Eskandari and Motamedi [59] carried out a literature review on diminished reality in architectural and environmental design. They identified challenges such as processing large amounts of data in large-scale environments, registration, and illumination consistency.

Strand Strand [60] conducted an SLR concerning the use of VR in architecture and engineering design. The author identified the need for proper functionalities for sketching and designing as a relevant challenge. This review examined 15 research studies published between 2015 and 2020. A literature review by Cruz and Dajac [61] addressed the application of VR in construction safety. The review encompassed 63 studies published between 2010 and 2020 and identified VR's inaccuracy, cost, maintenance needs, and technical complexity as factors that challenge its use. Fenais et al. [62] produced an SLR on the application of AR to underground construction and identified the main challenges and possible solutions. The set of challenges included data collection, modeling, hardware limitations, tracking, and managing data. The work by Fernandez et al. [56] highlighted as adoption barriers the cost of technology, hardware issues, and the application development process.

The current SLR also synthesizes the main hurdles researchers may face when addressing XR in AEC. With that objective, a dedicated classification methodology is presented. Furthermore, the evolution of those limitations and challenges over the analyzed period is tracked.

One of the main objectives of a literature review is the identification of trends to support future research activities. Wen and Gheisari [63] conducted an SLR exploring VR use for communication purposes in the AEC area. They analyzed 41 studies published over 15 years. They identified the real-time data transfer between BIM and VR applications, VR/AR integration, and increased realism as future trends. Song et al. [64] carried out a literature review of AR in digital fabrication in architecture. They analyzed 84 studies published between 2010 and 2020 to gain insights into the current state-of-the-art. Among the future trends identified are multi-operator participation, real-time scanning, and better tracking precision.

Prabhakaran et al. [65] addressed immersive technology use in the architecture and construction industry. They evaluated 51 studies published between 2010 and 2019. The studies were classified according to the technology used, construction project stage, system maturity, and collaborative nature. The authors identified a set of directions for future research, including multi-sensory feedback. Rankohi and Waugh [47] analyzed, using a structured methodology, 133 papers published before 2012. The papers were categorized according to the industry sector, target audience, project stage, application area, and technology, among other factors. The objective was to synthesize the state-of-the-art and identify trends. They highlighted web-based mobile AR systems for on-site construction monitoring as a future trend. The authors stepped up their research with 2013 and 2014 complementary reviews on VR in AEC [66] and on the comparison between the role of VR and AR in AEC [67].

The current SLR further expands the scope of trend identification used in the previously mentioned works by analyzing the evolution of multiple aspects of XR and AEC. Such aspects include XR hardware characteristics mentioned in primary studies, the evolution of studies by AEC fields, research approaches, challenges, and benefits.

3. Review protocol and methodology

The review protocol and methodology for this study are based on the work developed by Kitchenham and Charters [1,68] and Brereton et al. [69]. The stages associated with conducting the SLR are detailed below.

3.1. Research questions

The research questions that this SLR is intended to answer are the following:

RQ1. How much XR activity in AEC has there been since 2011?
RQ2. Which areas of AEC have had the most contributions in the period analyzed?
RQ3. Which types of XR technologies have been used the most?
RQ4. What are the benefits of using XR in AEC?
RQ5. What are the limitations and challenges that hinder the research of XR in AEC?

3.2. Search strategy

The search for primary studies was carried out using the Scopus electronic library (https://www.scopus.com). The Elsevier publishing company manages Scopus, which contains metadata of more than 82 million documents and has more than 1.7 billion references.[6]

The selected source was searched for primary studies using relevant search terms. These search terms were chosen following a series of iterations to improve the search strategy, as advised by Cooper et al. [70]. They aggregate relevant concepts by combining XR terms (*e.g.,* 'virtual reality') with AEC field names (*e.g.,* 'civil engineering') and other AEC terminology (*e.g.,* 'concrete structures'). The search string used for querying Scopus is the following:

> TITLE-ABS("virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "diminished reality") AND TITLE-ABS("civil engineering" OR architecture OR construction OR "aec" OR "BIM" OR "structural design" OR "structural analysis" OR "structural engineering" OR "seismic" OR bridge OR dam OR highway OR pavement OR tunnel OR geote* OR hydr* OR sewer OR coastal OR municipal OR "environmental engineering" OR "facility management" OR "urban design" OR "urban planning" OR "landscape design" OR restoration OR "concrete construction" or "concrete structures" OR "steel construction" OR "steel structures" OR "rebar" OR "wood structures" OR "wood construction" OR masonry OR glazing OR carpent*)

This search string was constructed using Boolean operators (*e.g.,* 'AND', 'OR') and wildcards (*e.g.,* '*'). AEC terms with broad meanings, like 'setting' or 'utilities', were not included as they would generate many irrelevant results. Some XR terms like 'diminished reality' were also not used as they produced no relevant results. The search covered free-text terms [70], including the title, abstract, and author-specified keywords.

3.3. Study selection criteria

The selection of relevant studies from among those found in the Scopus search followed a multistage approach, as advised by Kitchenham [1]. This approach is illustrated in Fig. 3. In the initial stages, the exclusion relied solely on screening bibliographic metadata (including dates, titles, and abstracts). On the contrary, the selection in the subsequent stages was based on the analysis of the full texts of the studies.

First, the studies were filtered by their publication date. Only studies published between January 2011 and December 2022 passed on to the next stage. The reason for establishing such a wide time interval was to have a meaningful panorama of the last decade regarding XR in AEC research. Next, the studies were filtered by the topics they addressed. Only studies whose primary focus is the use of XR in AEC were selected.

The following stage consisted of addressing duplicate studies. Duplicate reports of the same study were excluded. Only the most complete versions among the duplicates were passed on to the next stage. Secondary studies were also excluded, as their analysis falls outside the scope of this study.

Studies in languages other than English were rejected. Before setting this criterion, language bias [1] implications were examined. The authors believe that some mitigating factors may hinder language bias's ill effects on this SLR's validity. First, the percentage of non-English studies in the Scopus digital library is small (less than 8% of all studies as of 2019, according to Vera-Baceta et al. [71]). And second, it is likely that a quality report in a non-English language has an English counterpart regarding the same study.

The next stage consisted of eliminating short-papers, posters, work-in-progress, and retracted/withdrawn papers. From the remaining studies, only those that were peer-reviewed were passed on to the next stage.

The following stages implied that full copies of the studies needed to be obtained. The studies whose copy could be obtained were filtered by the number of pages. Studies with four or fewer pages (including bibliographic references) were excluded. The remaining studies were assessed for their actual relevance. This assessment identified studies that provide direct evidence regarding the research questions.

The decision on the inclusion/exclusion of studies was based on the agreement between the researchers who author this SLR. This agreement was measured using Weighted Kappa [72]. Disagreements on the inclusion/exclusion were resolved with further analysis of the study and its framing within the scope of the defined protocol.

3.4. Data extraction

A data extraction procedure was designed to ensure the collection of all relevant information needed for addressing the research questions and assessing the quality of primary studies. Each study was analyzed, and its information was extracted independently by at least two authors, as advised by Kitchenham and Charters [68]. Consistency was assessed using control studies which all the authors analyzed. Disagreements were resolved by involving a third author in the analysis.

3.4.1. Data collection form

The extracted information was recorded using a data collection form. The fields of this form and corresponding example values are shown in Table 1. In addition to the information needed for assessing the research questions and the quality, the form also includes standard fields. These fields contain information regarding *e.g.,* the name of the reviewer and date of extraction.

The correspondence between the research questions and the information extracted is shown below:

- RQ1: F5, F9, F10, F11, F14, F22
- RQ2: F5, F8, F12, F13, F15
- RQ3: F5, F16, F17, F18, F19
- RQ4: F5, F12, F16, F20
- RQ5: F5, F21

Further context to the 'non-standard' fields (F10–F22), including the definition of appropriate taxonomies, is presented in the following sections.

3.4.2. Study research approach

The selected studies follow distinct research approaches. As such, they were categorized using the classification methodology developed by Wieringa et al. [73] and adopted by Vilela et al. [74], Petersen et al. [75], and Tiwari and Gupta [76]. This classification frames studies in the categories shown in Table 2. Some studies span more than one category.

3.4.3. Study contributions

The primary studies addressed in this SLR were also analyzed for their type of contribution. For that purpose, a classification methodology similar to the one proposed by Petersen et al. [75] and used by Vilela et al. [74] was adopted. This classification frames studies in one or more contribution categories (shown in Table 3). The set of contribution categories (SC1–SC18) was refined (categories were added or removed[7]) throughout the execution of this SLR per its occurrence in the analyzed studies.

[6] Scopus content: https://www.elsevier.com/solutions/scopus/how-scopus-works/content.

[7] Only a single contribution category, 'Datasets', was removed. Contributions related to the production of metrics were encompassed in the category 'Metrics'.

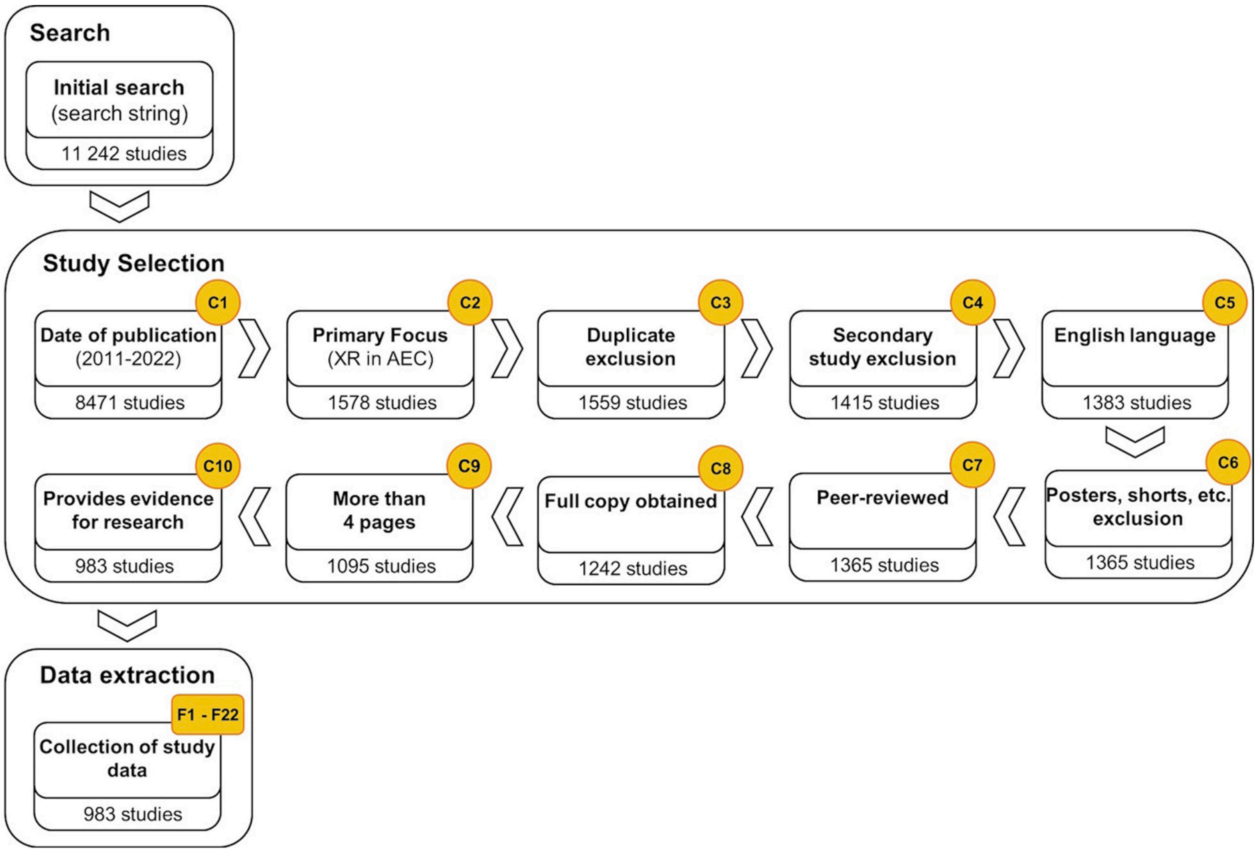

Fig. 3. Diagram of the primary studies search, selection (C1–C10 inclusion/exclusion criteria), and data extraction (F1–F22) stages. Includes the number of studies that resulted from each stage.

Table 1
Data collection form (with example values).

#	Data item	Example value
F1	Names of reviewers	Trindade, Ferreira
F2	Date of data extraction	2022–12–21
F3	Study identifier	Samuel2022
F4	Title	Defect-oriented supportive bridge inspection system featuring building information modeling and augmented reality
F5	Year	2022
F6	Authors	Samuel I.J., Salem O., He S.
F7	Publication	Innovative Infrastructure Solutions
F8	Author keywords	augmented reality, bridge inspections, building information modeling, defect information, supportive systems
F9	Country of first author	USA
F10	Research approach	Evaluation study, Validation study
F11	Study contributions	Tool, Metrics
F12	Areas/fields of application	Engineering: Structural engineering, Civil engineering
F13	Use environments	On-site
F14	Tested in real/realistic environment	Yes
F15	Type of structure	Bridge
F16	XR technology	Augmented reality
F17	XR display	2D display
F18	XR input	Touch screen
F19	XR feedback	Video
F20	Cited benefits	Accuracy
F21	Cited limitations	Equipment
F22	Quality score	$1.0 \leftarrow \sum\{1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0\}/9$

3.4.4. Study quality assessment

The assessment of the quality of primary studies was undertaken. This assessment aims to quantify the relative importance of primary studies for guidance in data synthesis and the interpretation of findings [68].

The term ‘quality’ is used, in this SLR, as the extent to which a study minimizes the risk of bias (internal validity), is generalizable and applicable (external validity) [74,77,78]. To that extent, a quality instrument was devised, consisting of a checklist of nine factors. These quality factors (enumerated in Table 4) are subjective by nature and were adapted from de Souza Cardoso et al. [79], and Egger and Masood [80]. Each factor was assigned a discrete numerical scoring scale, allowing a straightforward quality quantification. This quantification enables the meta-analysis of the studies.

Table 2
Research approaches [73].

#	Research approach	Description
RA1	Evaluation study	Documents the investigation or implementation of an existing technique in practice. It often includes case or field studies.
RA2	Solution proposal	Proposes a novel technique (or a significant improvement of an existing technique) and argues its relevance without a full-blown validation.
RA3	Validation study	Investigates the properties of a solution that has been proposed elsewhere and still needs to be validated.
RA4	Philosophical study	Proposes a new way of looking at things using *e.g.,* a conceptual framework.

Table 3
Study contributions.

#	Contribution	Description
SC1	Approach	Proposed strategy for solving a particular problem.
SC2	Architecture	Overall design and organization of a system or application.
SC3	Checklist	List of tasks to be completed for a particular activity.
SC4	Comparison	Evaluation of strengths and weaknesses of different solutions.
SC5	Discussion	Critical analysis and interpretation of a particular topic.
SC6	Framework	Conceptual structure used to solve a specific problem.
SC7	Guidelines	Best practices for achieving a specific outcome.
SC8	Language	Set of rules and syntax used to express information.
SC9	Method	Systematic and repeatable procedure for achieving a goal.
SC10	Methodology	Overall principles for conducting research or solving a problem.
SC11	Metrics	Quantitative measures to assess performance or effectiveness.
SC12	Model	Simplified representation of a real-world system.
SC13	Process	Series of actions required to accomplish a specific result.
SC14	Protocol	Set of rules that govern the exchange of information.
SC15	Technique	Specific procedure used to solve a particular problem.
SC16	Template	Pre-designed format used as to produce standardized outputs.
SC17	Tool	Software application used to perform a specific task.
SC18	Workflow	Sequence of activities required to complete a specific project.

Table 4
Quality factors.

#	Quality factor
QF1	Are the objectives of the study clearly stated?
QF2	Is the context in which the study was carried out adequately described?
QF3	Is the methodology of the study clearly explained?
QF4	Is related work adequately addressed and discussed?
QF5	Is there an appropriate discussion about the results of the study?
QF6	Are the benefits of the research understandably pointed out?
QF7	Are the limitations and challenges of the research distinctly pointed out?
QF8	Are the findings of the study clearly described?
QF9	Is there a clear connection between data, interpretation, and conclusions?

The scoring criteria for quality factors are as follows:

$$Score_{QF} = \begin{cases} 0.0 & <= \text{ If the quality factor is not met} \\ 0.5 & <= \text{ If the quality factor is partially met} \\ 1.0 & <= \text{ If the quality factor is fully met} \end{cases}$$

The quality of each study (0–1) is given by the sum of the score of the quality factors divided by the number of factors:

$$Quality = \frac{\sum_{n=1}^{9} Score_{QFn}}{9}$$

In this SLR, quality was not used for the inclusion/exclusion of primary studies.

3.4.5. Field of application

Each primary study was framed within the context of one or multiple fields of application. A multi-level taxonomy (classification tree) of application fields was devised to ensure consistency (Fig. 4). This taxonomy was based on the work developed by El-Diraby et al. [81], Lou and Goulding [82], Kızılyaprak and Altun [83], and in the ISCO-08 occupations standard [84]. The top level of the taxonomy corresponds to the three main areas of AEC: architecture, engineering, and construction. The subsequent level represents the specific fields of each of the top-level areas.

The taxonomy has been systematically refined throughout the execution of this SLR following the occurrence of the fields in the analyzed studies. In particular, flooring, glazing, painting, and tile setting were removed from the taxonomy's initial version because no studies addressed these construction fields.

Although some of the fields of the proposed taxonomy are often identified as separate areas *e.g.,* facility management[8] or environmental engineering, in this SLR, for simplification and better structuring of the taxonomy, they were considered as fields of the area of engineering.[9]

The taxonomy also contains categories that have varying scopes, with some being broader (such as civil engineering) and others being narrower (such as municipal engineering). This arrangement enables the maintenance of infrastructure and services provided by local government entities to be classified as municipal engineering, while generic non-municipal public works can be included in civil engineering within the proposed taxonomy.

[8] The term 'facility management' is often aggregated to AEC by using the acronym AEC/FM.

[9] Facility management involves elements of the three areas of AEC (particularly when it comes to planning and design). However, one could argue that because it requires expertise in fields such as HVAC systems, electrical systems, piping system inspection and design, and building automation systems, it is closer to engineering than to the other two areas of AEC.

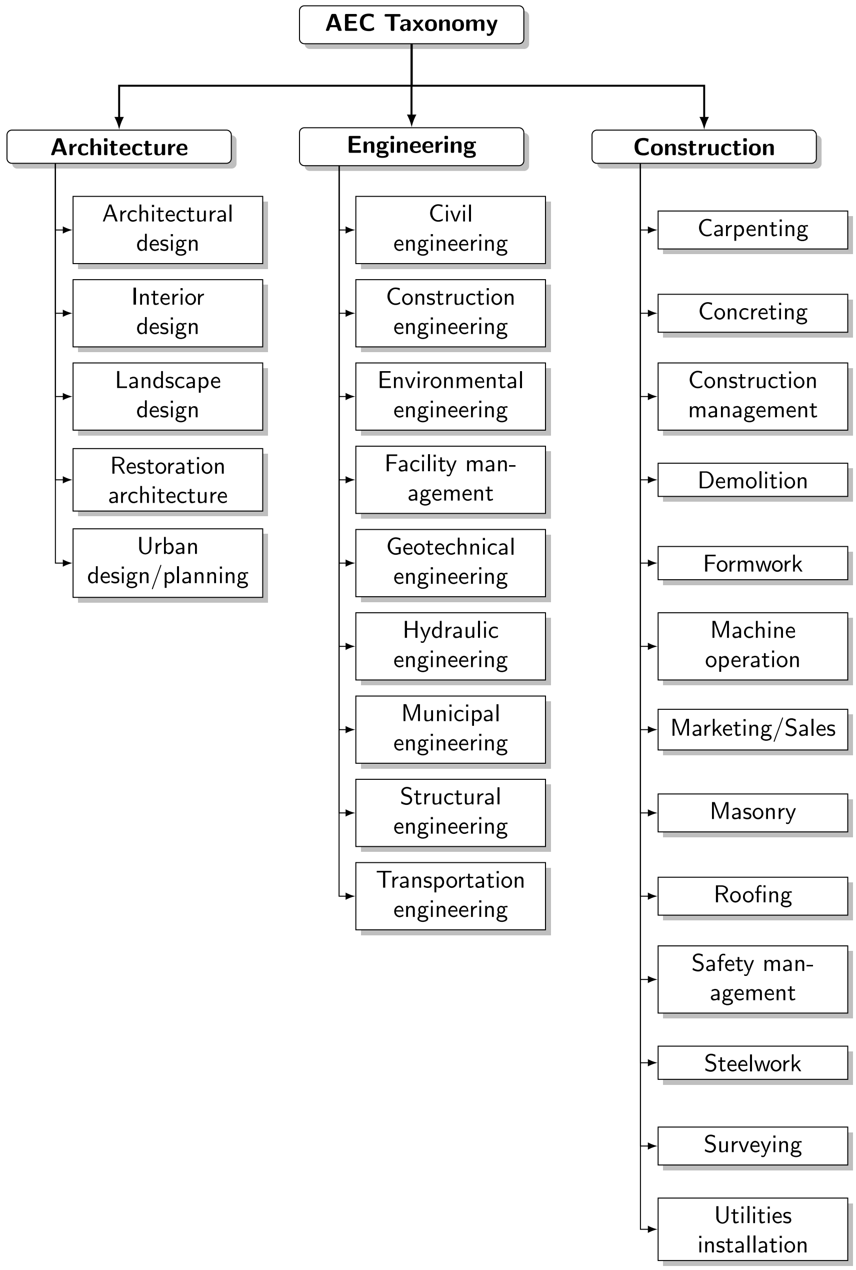

Fig. 4. AEC taxonomy.

The representation of the fields of application in the data collection form (Table 1) uses the following notation:

$< area_1 >, \dots < area_x >:< field_1 >, \dots < field_y >$

e.g., engineering: civil engineering, structural engineering

3.4.6. *Type of structure*

In addition to the field of application, the primary studies were also classified in terms of the types of structures they address. For that purpose, a dedicated classification methodology was developed. This classification was based on the methodology proposed by Eurostat Commission of the European Communities (Statistical Office/Eurostat) [85]. Such a classification effectively identifies the particular object of a given study. For example, a study framed in the structural engineering field could address many different structures, like buildings, bridges, or dams.

The classification of the type of structure has been refined throughout the development of this SLR per the occurrence of different kinds of structures[10] in the analyzed studies. This classification is represented in Table 5.

3.4.7. *XR technology*

The extraction of information regarding XR technology associated with each primary study was also carried out. For that purpose, a specific taxonomy was created (Fig. 5). This taxonomy was based on the work developed by Motejlek and Alpay [86], Parveau and Adda [87], Flávian et al. [88], Mann et al. [89], Muhanna [90] and Hugues et al. [91]. The taxonomy addresses features considered relevant for a comprehensive characterization of each study. The set of features includes the type of XR reality (*e.g.,* AR, VR), the display used (*e.g.,* HMD, 2D screen), the type of input used (*e.g.,* keyboard and

[10] Airports did not have any occurrence in the studies analyzed, so they were not included in the classification categories.

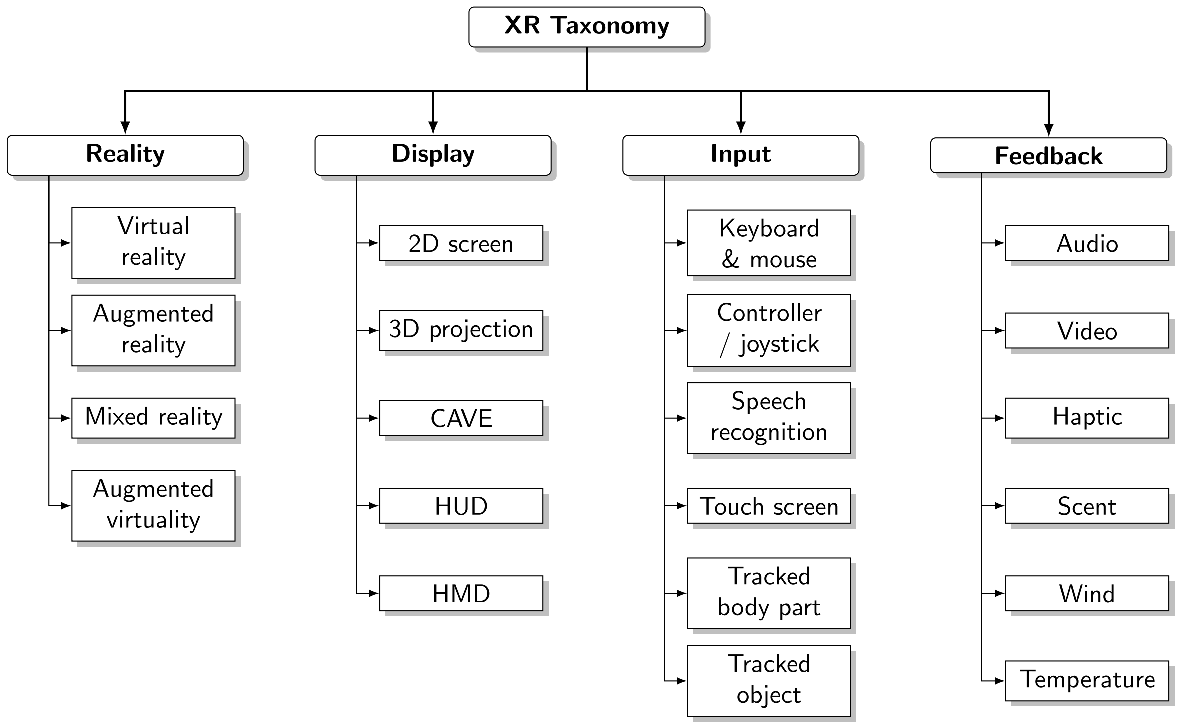

Fig. 5. XR taxonomy.

Table 5
Type of structure.

#	Type of structure
TS1	Bridge
TS2	Building
TS3	City/landscape
TS4	Dam
TS5	Highway/road/railway/bicycle path
TS6	Industrial facility
TS7	Marine/fluvial structure (port, dock, harbor, jetty)
TS8	Municipal service (sewer, water, gas networks)
TS9	National infrastructure services (power, telecommunications)
TS10	Sports arena
TS11	Soil/rock structure
TS12	Tunnel
TS13	None/general

Table 6
Cited benefits of the research.

#	Type of benefit
BE1	Increases operability/reliability
BE2	Increases safety
BE3	Improves accuracy
BE4	Improves efficiency/efficacy/effectiveness/productivity
BE5	Decreases time
BE6	Decreases costs
BE7	Decreases waste
BE8	Reduces mental/physical effort, improves convenience, practicability
BE9	Improves decision making/choice
BE10	Promotes participation, engagement
BE11	Improves system interoperability/integration/data exchange
BE12	Improves team work/management/communication/organization
BE13	Improves user experience/usability/convenience
BE14	Improves learning/learnability/understanding
BE15	Improves motivation, creativity
BE16	None cited

mouse, tracked object,[11] tracked body part), and the type of feedback (*e.g.,* audio, haptic).

3.4.8. Benefits

A classification methodology was also adopted and extended to categorize the possible benefits cited in studies. This classification was based on the work developed by Carnevalli and Miguel [92] and expanded to encompass other situations encountered in the analyzed studies. The classification for the cited study benefits is represented in Table 6.

3.4.9. Limitations and challenges

A classification methodology was equally developed to categorize the limitations and challenges mentioned in the studies. It was based on the work of Purssell and McRae [93] and Jesson et al. [94] and extended by encompassing the several situations encountered in the analyzed studies. Limitations are understood in this SLR as difficulties encountered when conducting a study, which somehow influence the results. Challenges are difficulties that were surpassed or did not influence the results [95]. The classification for the limitations and challenges pointed out in the studies is represented in Table 7.

3.5. Data synthesis

The data extracted from primary studies was synthesized for qualitative and quantitative analysis. The descriptive data was aggregated in tables designed to highlight common aspects and heterogeneities between studies [68]. This aggregation was also executed to contextualize the extracted information in the scope of the research questions, which facilitates conclusions in that respect. Furthermore, a meta-analysis of the data was carried out. Statistical methods and techniques were used to obtain suitable derived measures. These measures provide a quantitative outline for answering the research questions. The derived measures also served as a base for designing relevant visual idioms

[11] Within the scope of this SLR, tracked-type VR controllers fall in the category of tracked objects.

Table 7
Cited limitations and challenges of the research.

#	Type of limitation
LI1	Insufficient sample size
LI2	Issues with sample selection
LI3	Issues with methods and techniques
LI4	Issues in the data collection process
LI5	Issues with the equipment/software used
LI6	Issues with location
LI7	Time constraints
LI8	Timing of the study
LI9	Limited financial resources
LI10	Limited access to existing literature
LI11	Limited access to adequate users
LI12	Lack or age of previous research studies on the topic
LI13	Conflicts arising from cultural bias and other personal issues
LI14	None cited

(charts and diagrams). These idioms are a straightforward instrument for the visual interpretation of results. The results of the analysis are presented in the next section.

4. Results and discussion

The search string mentioned in Section 3.2 was used to search the Scopus electronic database. A search was initially carried out on April 9th, 2022, and successively updated with new results at subsequent dates until December 29th, 2022. The set of searches resulted in 11242 studies found.

Next, the study selection criteria (C1–C7) described in Section 3.3 were applied, resulting in 1366 studies.

The application of the remaining criteria required obtaining full copies of the studies (C8). The retrieval was successful for 1243 studies. Approximately 9% of C1–C7 criteria compliant studies could not be obtained despite reasonable efforts being carried out in that direction. The main barriers to retrieving studies were their location behind disproportionately expensive paywalls or on sites inaccessible to the general public (*e.g.,* participant-reserved areas on conference websites). The authors of the missing studies were contacted via email,[12] and full copies of the studies were requested. About 24% of the initially unobtainable studies were successfully retrieved using this strategy. For 73% of the unobtainable studies, authors were unresponsive, and for 20%, authors were inaccessible (*e.g.,* undelivered email). For the remaining 7% of the unobtainable studies, authors were uncooperative (responded but did not provide the studies).

From the studies for which complete copies were obtained, the elimination of those with less than four pages[13] and those that did not provided direct evidence for the research questions (C9–C10) resulted in a final number of 983 primary studies fully meeting the ten inclusion/exclusion criteria (Fig. 3). The complete list of selected studies is available online at: https://xr4dams.tecnico.ulisboa.pt/xr-aec/. These studies were passed on to the following stages of analysis for further assessment.

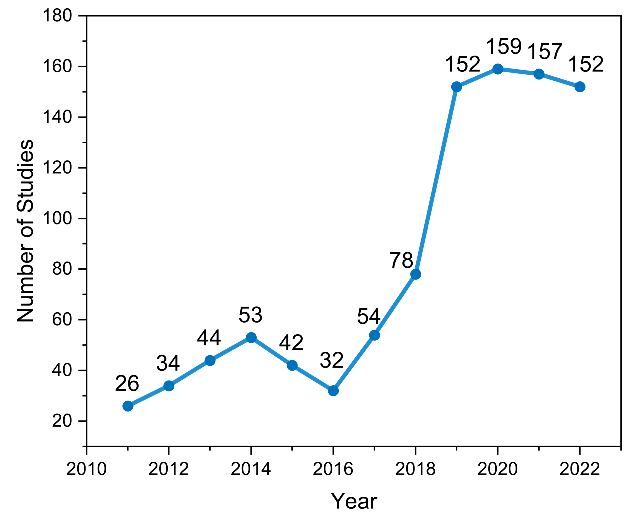

Fig. 6. Evolution of the number of relevant primary studies (published 2011–2022).

4.1. RQ1: XR activity in AEC

This research question aims to provide an updated overview of XR in AEC by means of quantifying the research activity in the last decade. As such, this section addresses the evolution of the volume of publications, its geographical distribution, prevalent research approaches, and main contributions.

The evolution in the number of publications from 2011–2022 is represented in Fig. 6. A steep increasing trend in published studies is noticeable between 2016 and 2019. From 2019 to 2022, a slowdown and stabilization to about 150–160 studies per year can be observed. This stabilization might be related to a consolidation of the novelty factor of XR in AEC (or XR in general). It can also be attributed to external factors like the onset of the COVID-19 pandemic in early 2020. One possible reason for the slight decrease in the number of studies in 2022 could be the delay in indexing by Scopus, as the studies were collected towards the end of that year (this aspect is elaborated upon in Section 5.2). Further studies would need to be conducted to assess these hypotheses. Nevertheless, the apparent stabilization in publications at an almost all-time high reveals the continued interest of the academic community in studying XR in the context of AEC.

Regarding the geographical distribution of research, the continents with the most publications are Asia (37.1%), closely followed by Europe (31.4%) and the Americas (25.4%). Africa and Oceania have the least studies published (1.3% and 4.8% respectively). The USA is the country with the most publications (196 studies), followed by China (134 studies) (Fig. 7). Although the number of published studies is not far for these two countries, its quality is significantly different. As such, the USA has an average quality of 0.87 and China of 0.65 (Fig. 8). From the analyzed studies, Canada is the highest-rated country in terms of quality, considering the top 20%[14] countries in number of studies produced.

An additional derived measure, *Field-normalized Productivity*,[15] was also devised to take into account that the number of studies produced by a country is strongly affected by its academic community

[12] Given the large number of authors that needed to be contacted, sending emails was automated using an application purposely developed for this SLR. The free application 'Auto Mailer' can be found at https://www.nunotrindade.com/software/auto-mailer.

[13] The number of pages of PDF files was calculated using an application specially developed for this work. Other available tools did not produce accurate results. The free application 'PDF Page Counter' can be found at https://www.nunotrindade.com/software/pdf-page-counter.

[14] Following the 80/20 rule of the Pareto Principle [96,97].

[15] This metric measures the number of XR in AEC studies produced by a country per researcher in that country, while taking into account the global average of publications per researcher in all fields. It was calculated using the following expression:

$$Field-normalized\,Productivity$$

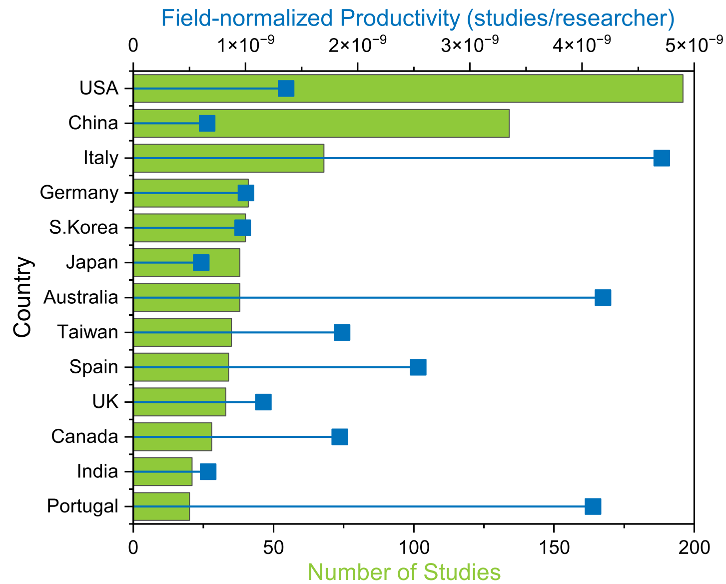

Fig. 7. Geographical distribution of primary studies for the 20% countries with the most studies (country of affiliation of first author), in green, together with the Field-normalized Productivity for each country (in blue).

size. By normalizing for the number of researchers, this measure allows for a fairer comparison of research output between countries with different population sizes and numbers of researchers. As such, it is worth highlighting the higher productivity in Italy (4.71E−09 studies/researcher), Australia (4.19E−09), and Portugal (4.10E−09) (Fig. 7). Japan (6.07E−10 studies/researcher), China (6.59E−10), and India (6.68E−10) have the lowest productivity of the top 20% countries with the most studies of XR in AEC.

In what concerns the research approach, the grand majority[16] of the analyzed studies are evaluations (732 studies) and validations (234 studies) (Table A.1).

Regarding study contributions (Table A.2), the most frequent type of contribution is the development of tools (SC17) (681 studies, 69%). This prevalence of tools as study outcomes might denote an increased demand, by the AEC area, for state-of-the-art instruments that can be used in production environments to support productivity improvements. Indeed, as will be discussed further on (Section 4.4), the improvement in efficiency/productivity (BE4) is one of the most sought-after types of benefits in the analyzed studies. Such a hypothesis is also supported by the high percentage of tools that are claimed by the authors to have been tested in real (*e.g.,* AR) or realistic (*e.g.,* VR) AEC environments (89% of studies that address tools, 61% of total studies). Nevertheless, the proportion of tools among the total number of cited study contributions has not evolved with a clear upward or downward trend over the analyzed period. The development of tools in the context of case studies is often associated with evaluation studies. That association can be observed in Fig. 9.

Comparisons (22% of studies) and metrics (15%) come after tools as the most frequent study contributions. These are primarily associated with validation studies (Fig. 9), which is the second most common type of approach. Similarly, philosophical studies are primarily associated with outcomes such as frameworks and discussions. On the contrary, solution studies result most often in tools and methods.

As some studies are associated with multiple approaches and contributions, a study can present *e.g.,* an evaluation and a solution proposal and result in both a tool and a discussion. Nevertheless, the distribution of contributions by type of research approach shown in Fig. 9 also seems to be mostly in accordance with the proposed approach definitions presented in Table 2.

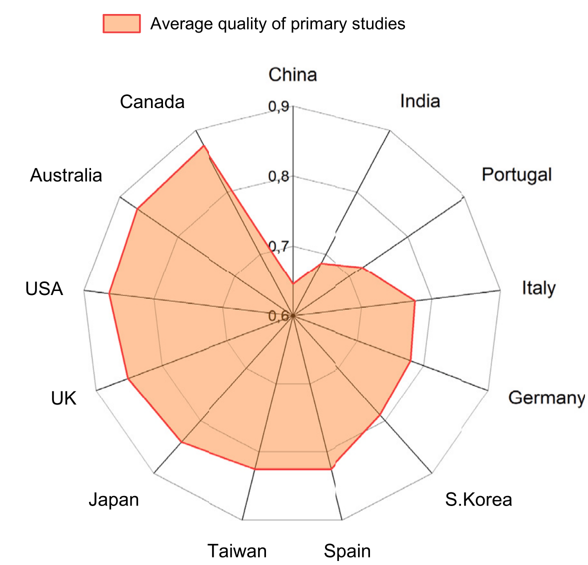

Fig. 8. Average quality of primary studies for the 20% countries with the most studies (country of affiliation of the first author). The average quality interval is limited to [0.6, 0.9] for a more understandable visualization.

4.2. RQ2: Areas with the most contributions

This research question aims to identify the areas, fields, and subjects of AEC where XR research has been focused the most. As such, this section analyses the evolution, tendencies, and relations between these different modalities of AEC and XR.

$$= \frac{Studies_{country}}{Researchers_{country}} * \frac{Studies_{total}}{Researchers_{total}} \quad (studies/researcher)$$

$Studies_{country}$ — Number of XR in AEC studies indexed by Scopus (2011–2022) produced by each country (affiliation of first author); $Studies_{total}$ — Number of XR in AEC studies indexed by Scopus (2011–2022) across all countries; $Researchers_{country}$ — Number of researchers (of all scientific fields) in each country [98,99]; $Researchers_{total}$ — Number of researchers (of all scientific fields) across all countries.

[16] It should be taken into account that studies can be classified into more than one type of approach.

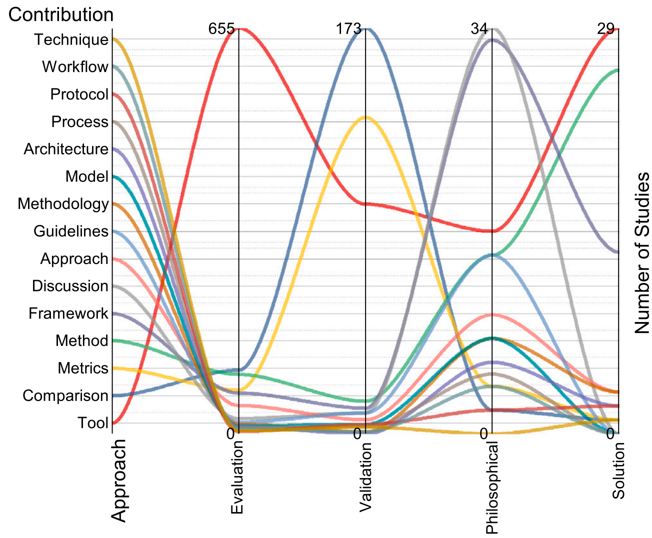

Fig. 9. Relation between the approaches and contributions of primary studies. The intersection values of the curves with the axes reflect the number of studies in which a given approach appears associated with a certain contribution (some studies are classified into multiple approaches and types of contributions).

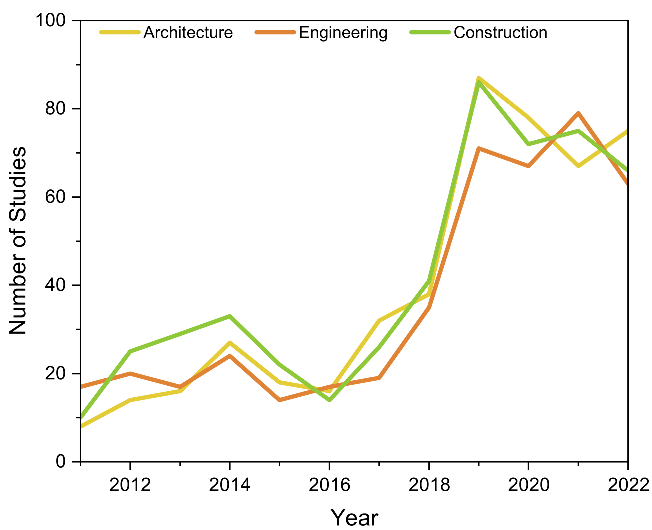

Fig. 10. Evolution of the number of XR primary studies for each AEC area.

Over the analyzed period, there was no substantial difference between the evolution of the number of XR studies produced in the three areas of AEC (Fig. 10). In fact, they interchangeably occupy the first, second, and third place during the last decade. The silhouette of the three curves is also very similar to the curve corresponding to the evolution of the total number of primary studies (Fig. 6). This similitude might indicate similar interest in XR across the three areas of AEC. Furthermore, a similar inference to the one in 4.1 can be made for the three areas, regarding the relative stabilization in publications, since 2019, at an all-time high.

The research volume evolution of the specific set of AEC fields considered in this work (Table A.3) is much more diversified than the general AEC areas previously mentioned. In the area of Architecture, the field with the most applications is Restoration Architecture (8.6% of total studies). It is closely followed by Urban Design (8.0%) and Architectural Design (7.2%). While Architectural Design has had an increase in the related number of studies in the last few years, Urban Design and Restoration Architecture show the inverse tendency (Fig. 11, shown in yellow). Indeed Restoration Architecture has been decreasing consistently since 2016. Urban design has reduced chiefly since 2013.

Regarding the area of Engineering, Structural Engineering and Civil Engineering are the most addressed fields (10.3% and 9.7% of total studies, respectively). The former has the highest number of studies from all AEC fields (101 studies). It also has had an apparent increase in research interest, at least since 2012 (Fig. 11, shown in blue). In opposition, the latter has seen a decrease in interest since 2015. Likewise, Facility Management (6.0% of total studies) and Transportation Engineering (3.3%) have seen a clear decline in research volume in the last few years. Municipal Engineering (1.4%) and Environmental Engineering (0.6%) are the fields with less expressiveness in the area of Engineering.

In what concerns the area of Construction, Construction Management is the field with the most research (9.6% of total studies). However, the XR research in this field has decreased and mostly stagnated in the last eight years (Fig. 11, shown in green). Likewise, the Machine Operation field (4.5%) has had a steady decrease in interest since 2011. In contrast, Safety Management (the second most productive field in the Construction area, with 8.7% of total studies) has shown a noticeable increase in scientific production since 2014. The rest of the fields in this area have a much lower representativeness than the three previously mentioned fields. Roofing (0.2%), Concreting (0.1%), and Demolition (0.1%) are the fields with the lowest amount of XR scientific production in the area of Construction.

Examining the author's keyword density of the analyzed studies also allowed the assessment of other relevant relations between XR technologies and AEC subjects (from the 793 studies that included author keywords, 2138 unique keywords were extracted). To enable a more abstracted visualization of the keywords density and affinity, the network plot[17] shown in Fig. 12 was built. As expected, this analysis revealed the very high significance of XR technologies such as 'virtual reality' (406 mentions) and 'augmented reality' (294 mentions) but also of AEC subjects such as 'BIM' (181 mentions). Furthermore, the network plot reveals a strong bond between XR technologies and BIM. This significance and bond seem to reflect both the relevance that BIM has had in the AEC area in the last decade and the interest of researchers and the industry in integrating XR and BIM.

The network plot in Fig. 12 also shows a significant use of education-related keywords. These include 'education' and 'training', but also more specific terms like 'engineering education', 'construction education' and 'safety training'. Furthermore, there is a noticeable bond between these terms and 'virtual reality', which seems to indicate a preference for VR over other XR technologies for AEC education/training. This apparent preference is in line with the percentage of studies that include classrooms (19.8% of total studies) as use-environment (Table A.4) and additionally mention the use of VR (12.7% of total studies). For AR and MR this percentage is 7.2% and 1.3%, respectively. Other subjects strongly connected with VR include 'urban planning' and 'construction safety'. AR on the other hand, is noticeably bonded with 'facility management' and 'cultural heritage'.

In what regards the types of structures addressed (Table 5, Table A.5), the vast majority of studies concern the use of XR in the context of buildings (Fig. 13). There is also a balanced amount of studies of XR applied to buildings for the three major areas of AEC (39.0% concern architecture, 32.4% engineering, and 28.6% construction). This distribution is somehow understandable, as, on the one hand, the construction of buildings is the most massively carried out type of structure worldwide. So even minor optimizations arising from the application of XR can bring immense benefits. On the other hand,

[17] The keyword frequency matrix needed for building the network plot was obtained using an application purposely developed for this SLR. The free application 'Keywords to Matrix' can be found at https://www.nunotrindade.com/software/keywords-to-matrix.

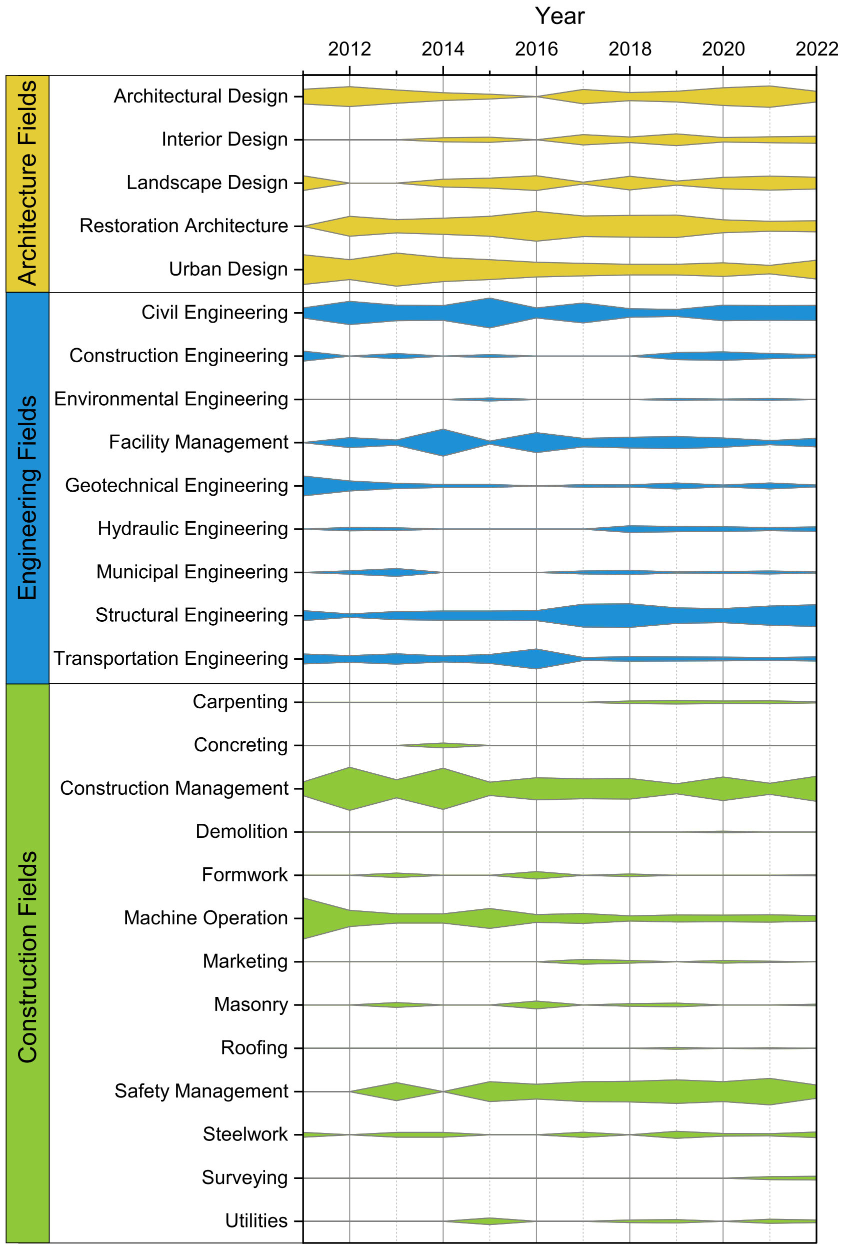

Fig. 11. Percentual evolution of the number of primary studies for the different fields of each AEC area. The percentage of each field is relative solely to the AEC area to which it belongs (*e.g.,* the percentage of the Urban Design field in each year is relative to the total number of studies in the Architecture area in that year).

the nature of building planning, design, and execution implies the participation of players from multiple areas of AEC, including architects, engineers, and builders. This interdisciplinarity is, of course, far from exclusive to buildings.

The studies of XR in the area of architecture are mainly focused on buildings (44.2% of studies in the architecture area). Another relevant type of structure in architecture studies is cities/landscapes (27.5%). This relevancy is most likely due to significant research in urban and landscape planning/design. XR studies in the area of engineering are, besides buildings (37.0%), closely distributed between other structures such as bridges (6.1%), roads (5.7%), tunnels (3.6%), and municipal services (3.2%). Cities (2.5%), soil structures (3.0%), marine structures (2.1%), and dams (2.1%) are also addressed. The least common structures in the engineering area are industrial facilities, sports arenas, and national infrastructures (1% or less). Studies in the area of construction are highly focused on buildings (35.4%). In addition, a significant amount of studies from the three areas are not focused on a particular type of structure.

4.3. RQ3: Usage of XR technologies

This research question aims to identify which XR technologies have been the most applied to the analyzed studies during the examined period. These include, as represented in Fig. 5, the type of reality used, the display, input mechanisms, and the feedback provided. As such, this section addresses the evolution and tendencies of these different types of XR aspects.

Globally, VR is the most addressed type of reality (Table A.6). Around 60.7% of total studies concern VR.[18] AR studies come next with 44.1%. The research of MR in AEC only encompasses 5.3% of the studies. AV has a residual use in the analyzed research (less than 1.0%).

The combined use of different types of realities also has some expression. Indeed, 9.0% of the studies combine the use of AR/MR and

[18] Some studies address multiple realities, types of display, input, and feedback.

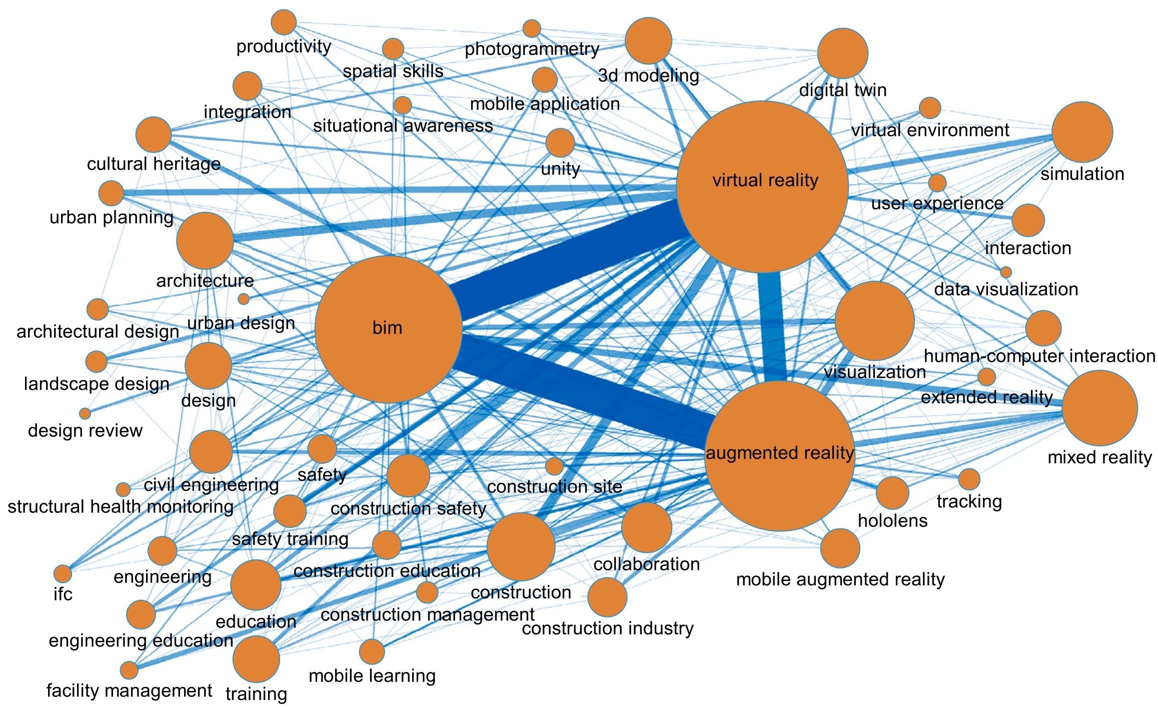

Fig. 12. Network of the top 50 most used author's keywords. The relative size of the circles encodes the number of times a keyword was used. The link thickness encodes the number of times that keywords appear together in the analyzed studies. Keywords with the same meaning (*e.g.,* 'vr' and 'virtual reality') were merged.

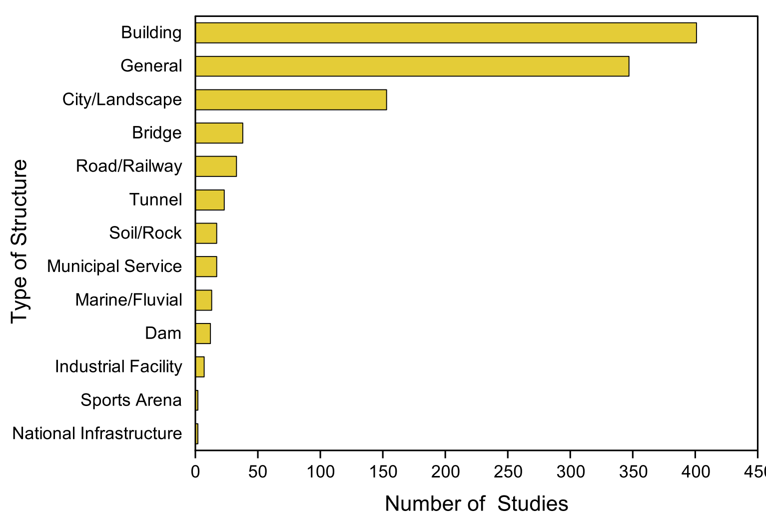

Fig. 13. Types of structures addressed in the analyzed studies. The 'General' type concerns studies that do not focus on a specific structure.

VR. This tendency is in line with Fig. 12, where a strong link between realities is noticeable. This combined use is, in the analyzed studies, often associated with collaborative systems. These systems promote teamwork between users located off-site (using VR) and users on-site (using AR/MR).

In Section 4.1, the growing tendency of the research of XR technologies in AEC was discussed. However, a significant difference between the growth of the distinct modalities of XR was observed in the analyzed studies. While percentually VR in AEC has been steadily growing since 2014, AR has been decreasing, as can be seen in Fig. 14. In addition, a proportional growth in MR research has accompanied this downward trend of AR.

With regards to the type of display (Table A.7), HMDs are the most often addressed (46.4% of the studies concern its use). They are followed by the use of 2D screens (41.6%). CAVE systems are covered in 3.4% of the studies and 3D projection in 2.0%. The use of HUD is still residual in AEC research (0.1%). Also, as expected, the use of more conventional types of display, like 2D screens and CAVE systems, has declined sharply (Fig. 15) over the analyzed period. Conversely, the types of displays specially designed for XR applications have increased. These displays include dedicated VR and AR/MR HMDs.

Concerning the type of input, the use of tracked objects, like tracked VR controllers, is the most common (31.1% of the studies discuss its use) (Table A.8). This input type is followed by touch (26.4%), used primarily in touch-sensitive 2D displays. The main input types in 15.3% of the studies are keyboard and mouse. Tracked body parts are present in 11.9% of the research. A still representative 7.7% of studies use traditional controllers and joysticks. A tiny percentage of the analyzed research takes advantage of voice recognition (less than 1%). This type

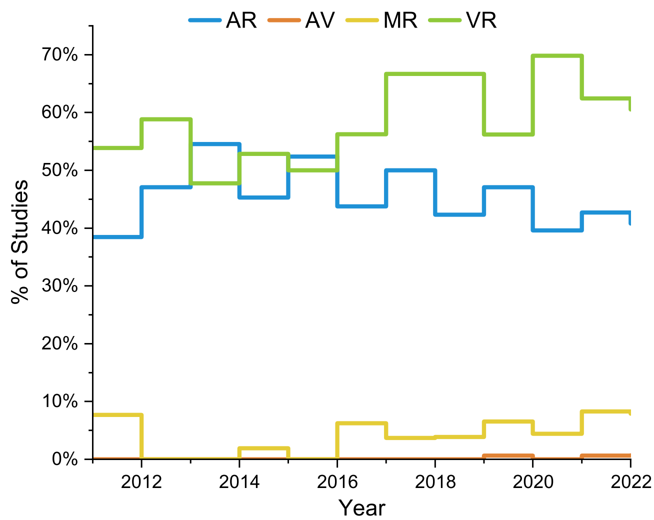

Fig. 14. Evolution in the percentage of studies by XR technology.

of input is mainly associated with AR/MR realities, as the Microsoft Hololens[19] HMD has voice recognition functionalities built-in.[20]

There has also been a noticeable change, during the analyzed period, in the type of input devices used in the research. While at the beginning of the last decade, keyboard& mouse, and touch screens were still the most used, that situation has been changing. In fact, there has been a swift transition to tracked objects and tracked body parts (including full-body-tracking), as can be observed in Fig. 16. This shift seems to indicate an increased preference for more natural types of interaction in XR. Such preference has likely been potentiated by the evolution to more usable, accurate and affordable input hardware.

Finally, in regards to the types of feedback mentioned, the grand majority of studies are limited to video feedback (85.8% of the studies address its application) (Table A.9). A much smaller percentage (14.1%) also mentions audio. Haptic feedback is used in 1.4% of studies. Finally, wind feedback has a very small (0.1%) representation.

4.4. RQ4: Benefits of XR in AEC

This research question aims to address the benefits to AEC of the application of XR technologies. With that purpose, the benefits cited in the analyzed studies are quantified and compared by AEC area and type of reality.

The most cited benefit overall (Table A.10) is the improvement of learning and understanding (27.2% of studies address it). This benefit is closely followed by the increase in efficiency and productivity (24.0%). The improvement in decision-making/choice (14.9%) and improvements in teamwork (13.3%) follow. With a similar number of mentions, participation/ engagement and user experience appear in 12.4% and 12.2% of the studies, respectively. Improvements in safety (11.2%), accuracy (9.0%), time savings (6.1%), operability (5.3%), cost (5.1%), motivation (3.9%), and interoperability (3.9%) are also cited. The reduction of effort (2.8%) and waste (0.8%) are the least mentioned benefits.

The distribution of benefits across XR realities presents some notable differences (Fig. 17). While learning is the most cited benefit in studies that address VR, for AR/MR this benefit appears only in second place. This difference is in line with the affinity between VR and education mentioned in Section 4.2 and illustrated in Fig. 12. For AR, the most cited benefit is the improvement of efficiency and productivity, followed by learning and teamwork. Standing out in MR studies, besides teamwork and learning, is operability. This incidence might be explained by the significant number of MR studies that address maintenance and facility management.

The distribution of the top benefits across the three AEC areas (Fig. 18) is similar. Indeed, learning and efficiency are the first and second (respectively) most addressed benefits in all areas. However, there are also other notable benefits that differ from area to area. One example is the promotion of participation and engagement in the architecture area. Another relevant difference is the high number of mentions of teamwork as a benefit in the engineering area. Finally, in MR, the increase in safety is the third most mentioned benefit. This aspect might be explained by the significant number of studies that use MR for safety management.

4.5. RQ5: Research limitations and challenges

This research question aims to synthesize the main hurdles that researchers may find when addressing XR in AEC. These hurdles are identified by the limitations and challenges mentioned in the analyzed studies. The synthesis of such information can serve as a basis for researchers to better understand the issues they can face when they propose to develop a study that involves the application of XR to AEC.

Obtaining the required data to support this research question was not a straightforward task. This difficulty was mainly due to authors very often not mentioning the limitations and challenges of studies. In fact, 64.6% of the analyzed studies do not address limitations and challenges. In comparison, only 8.9% of the studies neglect to mention the benefits of the research.

The most mentioned limitation (Table A.11) is, by far, issues with equipment and software (mentioned in 24.0% of the studies). Other relevant limitations are issues with methods and techniques (11.7%), insufficient sample size (7.7%), and issues with sample selection (6.2%). The rest of the cited limitations are much lower (1.2% or less), including conflicts arising from bias, issues in the data collection process, limited access to adequate users, and time constraints.

A noticeable tendency can also be inferred regarding the evolution of limitations and challenges. While in the period from 2011–2017, equipment issues were pointed out as a limitation in up to 90% of the studies (where limitations were mentioned), that percentage has been decreasing heavily in the most recent years (Fig. 19). In opposition, issues with methods and techniques, insufficient sample sizes, and issues with sample selection have increased in the last decade. This contrast may indicate that XR hardware, software, and technology, in general, are becoming less of a hindrance to researching and testing practical XR solutions for AEC.

5. Conclusion

This study was designed to provide a thorough overview of the research on XR within the AEC area over more than a decade. The study was carried out through a SLR. It consisted on the analysis of 983 primary studies. These primary studies have been published over a period spanning 12 years (2011–2022). The SLR starts with the analysis of related work. The definition of the review protocol and methodology follows. This methodology includes the proposal of taxonomies for XR technologies, AEC fields, and other characteristics of the primary studies. The SLR continues with the presentation and discussion of the analysis results in the context of the proposed research questions. Finally, the limitations and challenges of the SLR are addressed.

The SLR results indicate that there has been a steady increase of XR research in AEC in most of the analyzed period, with a stabilization in the last four years. The evolution in the number of studies for the three areas of AEC also seems similar. The results also suggest that the geographical distribution of the number of studies is not coincidental

[19] Microsoft Hololens: https://www.microsoft.com/en-us/hololens.
[20] Hololens voice input: https://learn.microsoft.com/en-us/windows/mixed-reality/design/voice-input.

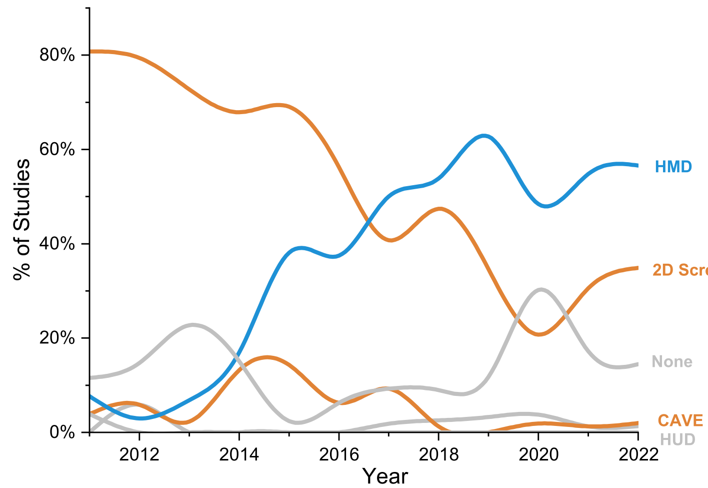

Fig. 15. Evolution (percentage) of the type of display addressed in studies. The category 'None' pertains to studies that do not specify the type of display (and instead address XR in AEC in a general way without tackling particular display types).

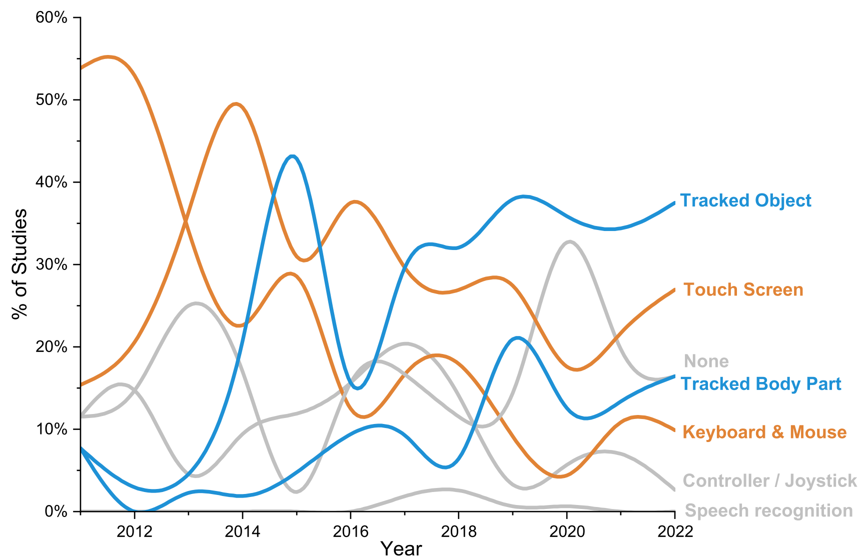

Fig. 16. Evolution in the percentage of studies by type of input. More natural types of interaction (object and body tracking) are on the rise (shown in blue). Traditional types of interaction (keyboard, mouse, and touch screens) have been declining (shown in orange). The category 'None' pertains to studies that do not specify the type of input (and instead address XR in AEC in a general way without tackling particular input types).

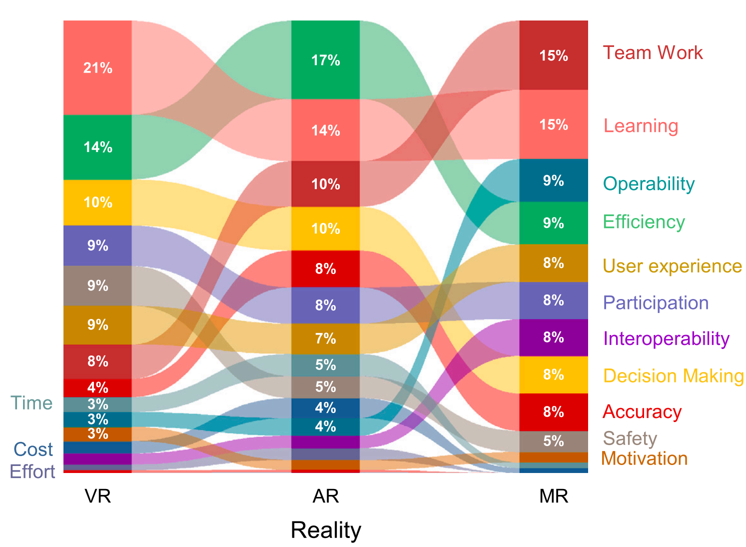

Fig. 17. Benefits of XR in AEC (percentage for each type of reality).

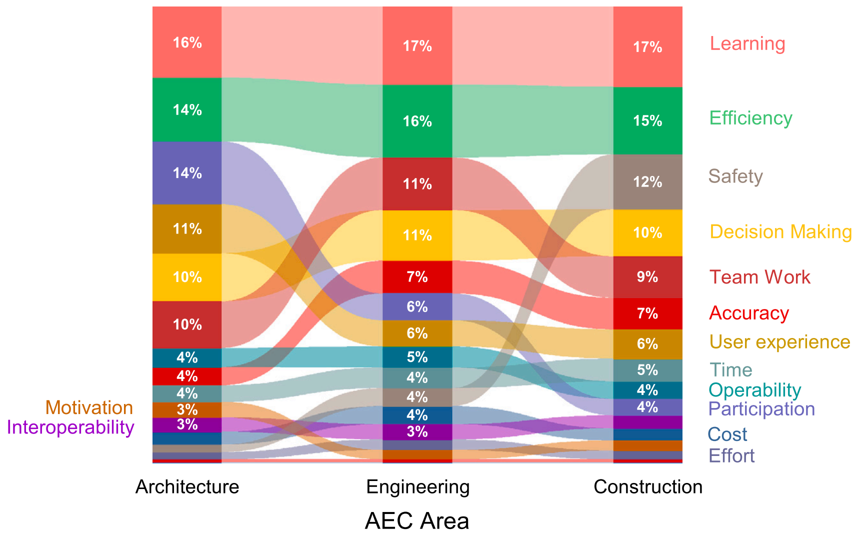

Fig. 18. Benefits of XR in AEC (percentage for each area of AEC).

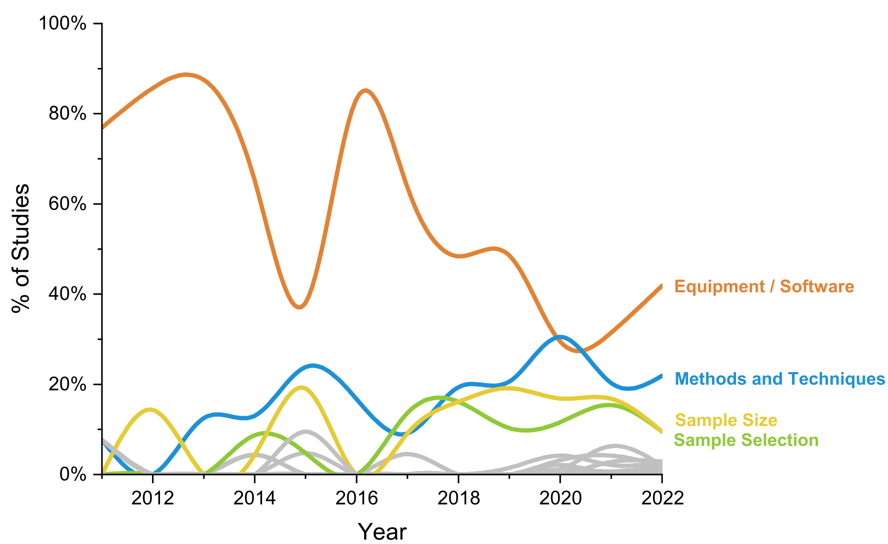

Fig. 19. Evolution of limitations and challenges cited in the analyzed studies (excluding studies where limitations and challenges were not cited).

with its quality. The most addressed subject, by volume of research, is BIM.

Some future trends for the research of XR in AEC can also be deduced. If the last five years are considered (following the criterion adopted by Rankohi et al. [47]), some fields of AEC seem to have been consistently increasing in popularity (in the form of the volume of publications). Examples of these fields are structural engineering, architectural design, and safety management. In opposition, some fields have been showing a consistent decrease. These include urban design, restoration architecture, civil engineering, facility management, transportation engineering, construction management, and machine operation.

Regarding future trends in the use of XR technologies, the results indicate that VR is still the most popular type of reality in what concerns AEC research. Moreover it has shown an increasing trend in the last 10 years. In opposition, AR shows a decreasing trend. Likewise, the use of HMDs is prevailing, to the detriment of more traditional types of display. In addition, the interaction has been transitioning from conventional to more natural types of input, like tracked objects and body parts.

Concerning the trends in research limitations during the analyzed period, the issues with equipment and software seem to be decreasing. This trend is likely due to the technological evolution in XR-related software and hardware. Regarding the research benefits, learning, efficiency, and teamwork are the most pointed out benefits in the studies.

5.1. Contributions and benefits

The main benefit of this SLR is (following the classification proposed in Table 6) the improvement of decision-making. On the one hand, it contributes to a more informed choice for future research work in this area. In that scope, the presented near-past evolution and future trends are especially relevant. On the other hand, it may serve as a knowledge base for the AEC industry professionals in making informed decisions when implementing XR systems. This SLR also has the additional benefit of improving the understanding (Table 6 classification) of the historical evolution of XR in AEC in the past 12 years. Such knowledge is fundamental for lessons learning and choosing paths to move forward in research.

The main contribution of this SLR is the presentation of an in-depth statistical and bibliometric analysis of existing literature regarding XR

Table 8
Electronic databases.

#	Database	Type	URL
DB1	Science Direct	Generic	https://www.sciencedirect.com/
DB2	Scopus	Generic	https://www.scopus.com/
DB3	Web of Science	Generic	https://www.webofscience.com/
DB4	Elsevier	Publisher specific	https://www.elsevier.com/
DB5	Emerald Insight	Publisher specific	https://www.emerald.com/insight/
DB6	Springer Link	Publisher specific	https://link.springer.com/
DB7	Wiley Online Library	Publisher specific	https://onlinelibrary.wiley.com/
DB8	ACM Digital Library	Professional	https://dl.acm.org/
DB9	IEEE Xplore	Professional	https://ieeexplore.ieee.org/
DB10	ASCE Library	Professional	https://ascelibrary.org/
DB11	ICE Virtual Library	Professional	https://www.icevirtuallibrary.com/
DB12	RIBA Library	Professional	https://riba.sirsidynix.net.uk/

Table A.1
Number of studies for each type of approach.

Approach	Number of studies
Evaluation study	732
Validation study	234
Philosophical study	96
Solution proposal	49

Table A.2
Number of studies for each type of contribution.

Contribution	Number of studies
Tool	681
Comparison	217
Metrics	151
Method	126
Framework	104
Discussion	78
Approach	58
Guidelines	42
Methodology	23
Model	22
Architecture	17
Process	16
Protocol	10
Workflow	10
Technique	6

Table A.3
Number of studies for each field of AEC.

AEC field	Number of studies
Structural Engineering	101
Civil Engineering	95
Construction Management	95
Safety Management	86
Restoration Architecture	85
Urban Design	79
Architectural Design	71
Facility Management	59
Landscape Design	50
Machine Operation	44
Interior Design	35
Transportation Engineering	32
Construction Engineering	28
Geotechnical Engineering	27
Hydraulic Engineering	22
Steelwork	16
Municipal Engineering	14
Utilities	10
Carpenting	9
Environmental Engineering	6
Masonry	6
Surveying	6
Marketing	5
Formwork	4
Roofing	2
Concreting	1
Demolition	1

Table A.4
Number of studies by use environment. The category ‘None’ pertains to studies that do not specify the use environment.

Use environment	Number of studies
Off-site	549
On-site	355
Classroom	195
None	6

in AEC research. It includes a set of methodologies, metrics, comparisons, and discussions (Table 3 classification). In that scope, the following aspects can be highlighted:

- The quantification of the evolution and current status of XR activity in AEC (related to RQ1);
- The identification of the AEC areas, fields, and subjects with the most research activity in XR (related to RQ2);
- A discussion and quantification of how XR technologies have been evolving over the last 12 years (related to RQ3);
- The systematization and quantification of research benefits (related to RQ4);
- The systematization and quantification of research limitations and challenges (related to RQ5);
- The identification of trends and future directions for XR research activity in AEC;
- The presentation of a set of XR and AEC taxonomies supported by previous secondary studies.

5.2. Limitations and challenges

This SLR suffers from a number of limitations and is associated with a set of challenges. These are enumerated below (using the classification proposed in Table 7):

- Limited access to existing literature: As mentioned in Section 4, the application of part of the study selection criteria required obtaining full copies of the primary studies. Due to several barriers, including the location of the studies behind paywalls (and despite the authors being contacted directly via email), not all the studies were obtained.
- Limited sample selection: The studies were obtained from a single online database, the Scopus digital library. Multiple databases should be considered to maximize the sample size of the available research and increase the likelihood of finding relevant studies [100]. The diversity of databases also allows the hampering of publication bias [77]. The usefulness of searching multiple databases, even when they contain the same studies, was addressed by Cooper et al. [70].;

Table A.5
Number of studies for each type of structure. The category 'General' pertains to studies that do not address a specific type of structure.

Structure	Number of studies
Building	401
General	347
City/landscape	153
Bridge	38
Highway/road/railway/bicycle path	33
Tunnel	23
Municipal service (sewer, water, gas networks)	17
Soil/rock structure	17
Marine/fluvial structure (port, dock, harbor, jetty)	13
Dam	12
Industrial facility	7
National infrastructure services (power, telecommunications)	2
Sports arena	2

Table A.6
Number of studies by type of reality.

Reality	Number of studies
VR	597
AR	434
MR	52
AV	3

Table A.7
Number of studies by type of XR display. The category 'None' pertains to studies that do not specify the type of display (and instead address XR in AEC in a general way without tackling particular display types).

Display	Number of studies
HMD	457
2D Screen	409
None	156
CAVE	33
3D Projection	20
HUD	1

Table A.8
Number of studies by type of XR input. The category 'None' pertains to studies that do not specify the type of input (and instead address XR in AEC in a general way without tackling particular input types).

Input	Number of studies
Tracked object	306
Touch screen	260
None	182
Tracked body part	117
Keyboard & mouse	151
Controller/joystick	76
Speech recognition	5

Table A.9
Number of studies by type of XR feedback. The category 'None' pertains to studies that do not specify the type of feedback.

Feedback	Number of studies
Video	844
None	139
Audio	74
Haptic	14
Wind	1

- Issues with methods: Relevant methodological issues concern the definition of the concept of 'quality' of primary studies (Section 3.4.4). The first issue is the strong subjectivity associated with such a type of quantification. The second issue is related to the adoption of a single set of quality factors (Table 4), instead of different factors for distinct types of study types. The former approach is used by Souza Cardoso et al. [79], and Egger and Masood [80] while the latter is suggested by Vilela et al. [74]. The authors of this SLR opted to use a single set to allow a straightforward quantification and comparison of the internal and external validity of all the studies;
- Issues in the data collection process/timing of the study: The most updated search in the Scopus digital library occurred at the end of 2022 (December 29th). Because there is a time lag between when a study is completed and published, and when it will appear in a generic database [101], it is very likely that some studies published in late 2022 were still not included in Scopus. As such, they could have been left out of this SLR;
- Time constraints: Although the sample size (983 studies) for this SLR was adequate (to the best of the author's knowledge, it is the most significant sample size ever used for an XR in AEC secondary study), it implied important challenges regarding the volume of data to handle. Several hundred articles had to be examined for every step of the study selection and data extraction stages. As such, time was a significant limitation in the execution of this work;
- Language bias: A final limitation worth mentioning is that only primary studies in English were addressed in this work. Non-English language studies were excluded from the analysis. This aspect of the SLR can lead to language bias, as pointed out by Kitchenham [1]. The mitigating factors of this limitation have been discussed in Section 3.3.

5.3. Future research

Potential directions for future research may include overcoming some of the limitations mentioned in Section 5.2. Below a few possible research directions are suggested:

- The expansion of the analysis by performing a broader search that includes multiple online libraries. Such a search can maximize the sample size and selection of the available research and increase the likelihood of finding relevant studies. A possible set of 12 electronic databases is shown in Table 8. This table includes three types of databases:
- Generic databases (DB1–DB3): These are extensive databases that comprise studies from multiple publishers and areas;
- Databases associated with specific publishers (DB4–DB7): These are databases managed by top publishing companies;
- Databases associated with professional bodies (DB8–DB12): These bodies include both computer science and AEC-related societies, associations, and institutes. Although, in addition to the selected ones, many other relevant bodies exist (*e.g.,* American Institute

Table A.10
Number of studies for each type of benefit.

Benefit	Number of studies
Improves learning/learnability/understanding	268
Improves efficiency/efficacy/effectiveness/productivity	236
Improves decision making/choice	147
Improves team work/management/communication/organization	132
Promotes participation, engagement	122
Improves user experience/usability/convenience	120
Increases safety	110
Improves accuracy	89
None cited	88
Decreases time	60
Increases operability/reliability	52
Decreases costs	50
Improves motivation, creativity	38
Improves system interoperability/integration/data exchange	37
Reduces mental/physical effort, improves convenience, practicability	29
Decreases waste	8

Table A.11
Number of studies for each type of limitation.

Limitation	Number of studies
None cited	636
Issues with the equipment/software used	236
Issues with methods and techniques	115
Insufficient sample size	76
Issues with sample selection	61
Conflicts arising from cultural bias and other personal issues	12
Issues in the data collection process	12
Limited access to adequate users	11
Time constraints	10
Limited financial resources	8
Issues with location	5
Lack or age of previous research studies on the topic	1

of Architects (AIA), Institution of Engineers (IEI)), they do not provide, to the best of the author's knowledge, suitable electronic databases.

- The development/adoption of a more robust and objective methodology for evaluating the quality of primary studies. This methodology should allow the comparison between different types of research approaches but also take into account their specificities;
- The analysis of further properties of XR (*e.g.,* the graphical engine used or the hardware characteristics of HMDs) in AEC studies;
- The comparison of the tendencies and evolution of XR in AEC with other areas where XR has been widely used. Examples of such areas are health, defense, and entertainment.
- The investigation of the relations between authors and between research centers in order to pinpoint hot-spots of XR in AEC research.

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 reported in this paper.

Data availability

Data will be made available on request.

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Appendix

See Tables A.1–A.11.

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