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Vertical extension of buildings: a systematic literature review

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ABSTRACT

The rising need for urban densification due to population demands and housing shortages has resulted in heightened interest in vertical extension (VE) of buildings. This paper presents a systematic review of 119 peer-reviewed articles analyzing VE research trends. The research employs content analysis, network visualization, and co-occurrence analysis to identify important terminology and definitions, thematic emphasis, and methodological approaches utilized in VE studies, across various temporal and spatial settings. The primary focus areas within the field are structural reinforcement, VE technologies, and suitability/impact considerations. Considering methodologies, the review demonstrates significant dependence on case studies and structural modeling to evaluate the feasibility and practical applicability. The study emphasizes the necessity for standardized VE taxonomy and recommends that future research should broaden its geographical scope to offer a thorough worldwide view on VE. The outcomes offer insights for urban planners, architects, policymakers, and academics, emphasizing key areas of attention and corresponding gaps.

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1. Introduction

The escalating growth of populations in cities highlights the imperative of implementing urban densification strategies to satisfy population demand (Amer et al. 2017). It is anticipated that the urban population will increase to 60% and 68% in 2030 and 2050, respectively (compared to 55% in 2019), as the global population is projected to reach 9.8 billion by 2050 (Argenziano et al. 2021; UN 2019). Consequently, future space demands may necessitate an additional 230 billion m^2 of floor area by 2060 (Ness 2023; Schmidt, Crawford, and Warren-Myers 2020). Likewise, the shortage of housing in several cities has generated an urgent need for innovative solutions that refrain from further urban infringement into greenfield or rural regions (Napieralska and Attia 2023). In response, urban densification has been advocated (UN 2017) with the potential to enhance social satisfaction and physical health, reduce energy and greenhouse gas emissions, and preserve green spaces (Julistiono, Oldfield, and Cardellicchio 2023b; Mouratidis 2019; Oldfield 2019; Resch et al. 2016).

Nevertheless, the scarcity of undeveloped sites and the complexities associated with brownfield redevelopment can make urban densification a challenging endeavour (Cappai, Forgues, and Glaus 2019; Julistiono, Oldfield, and Cardellicchio 2023b). Accordingly, the vertical extension (VE) of buildings, which involves adding extra floor(s) to existing structures (see Figure 1), has acquired significant traction within urban densification, assisting cities in addressing space needs while reducing their environmental impact (Daher, Kubicki, and Marvuglia 2023). Despite the technical difficulties (such as structural constraints (Cherkas and Rimshin 2017)) and regulatory obstacles (Napieralska and Attia 2023), this approach is increasingly viewed as a crucial strategy to solve the shortage of urban land, make the most of the current infrastructure, and lessen urban sprawl (Amer et al. 2017; Sundling 2019).

According to recent studies, VE enhances the sustainability objectives of urban regions by minimizing the necessity for demolition and new construction, hence conserving the embodied energy of existing structures (Bertolazzi et al. 2019). It provides an affordable option by enhancing the spatial capacity of currently constructed buildings (Napieralska and Attia 2023) by using their airspace and mitigating additional land consumption (Choi, Kim, and Cho 2020). Additionally, VE has the potential to improve the sustainability of urban buildings by incorporating modern and energy-efficient materials into older structures, thereby making them more resilient and environmentally friendly (Soikkeli 2016). It serves as a method to conserve architectural history while enhancing the functionality of historic structures (Cherkas and Rimshin 2017). Similarly, in highly populated regions where urban sprawl is a significant challenge, VE can optimize the utilization of existing infrastructure, and as a result, can reduce the necessity for outward growth (Soikkeli 2016). Consequently, vertical building extensions provide a rational strategy for urban development, harmonizing the necessity for urban expansion with the sustainability

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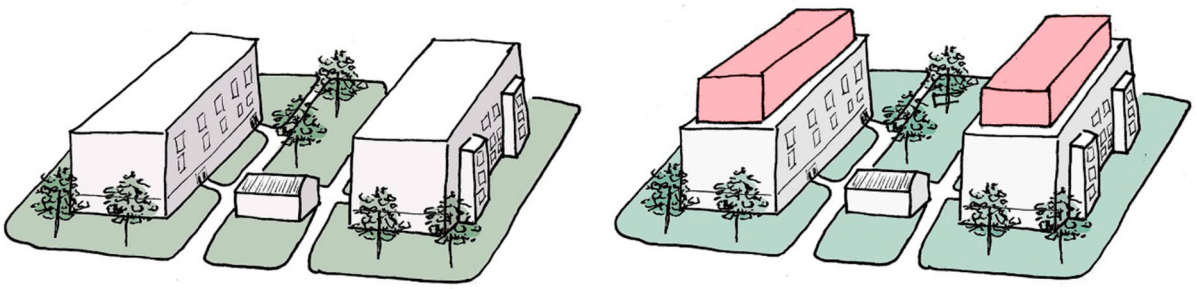

Figure 1. Vertical extension general scheme; reproduced from the work of Karjalainen, Ilgın, and Somelar 2021b.

requirements employing "environmentally conscious" principles (Khodadad et al. 2018).

Despite not being a new concept in practice (Artés, Wadel, and Martí 2017; González-Redondo 2022), VE might be regarded as a relatively new area of study since it has become a more attractive alternative due to recent advancements in building and construction technologies. Although previous research has examined various VE-related topics, limited effort has been made to combine these findings into a coherent study. Only a few review articles have been published in the field of VE in the built environment. For instance, a recent study by Julistiono, Oldfield, and Cardellicchio (2023a) investigated the construction, structural, and architectural strategies and trends of VE by reviewing more than 170 projects worldwide. Using literature review, interviews, and pilot surveys, Amer and Attia (2019b) identified 37 sustainable criteria for VE construction decision-making. Karjalainen et al. (2021a) evaluated residents' attitudes towards VE in Finland using a literature review and surveys. Soikkeli, Ilgın, and Karjalainen (2022) illustrated various stages and advantages of wooden VE in their study utilizing both literature and interviews. Additionally, Amer, Mustafa, and Attia (2019b) developed a conceptual framework for VE off-site constructions by reviewing the literature and case projects and also performing interviews with experts.

The aim of this article is to offer a fresh viewpoint by elucidating the evolution of discourse around VE and delivering a comprehensive examination of the methodology utilized in existing investigations, which, to our knowledge, has not been done previously. Accordingly, our main research question is: What are the key definitions, thematic emphasis, and methodological approaches utilized in VE studies, and how are they assessed across various temporal and spatial settings? To answer this, we performed a comprehensive systematic analysis of 119 peer-reviewed papers indexed in Scopus and Web of Science. The article contributes to the existing body of knowledge by employing a novel methodological approach to analyze the thematic and methodological trends in VE research.

This article is primarily meant for academics and researchers who are interested in the vertical extension of buildings, with a particular concentration on how the discussion around VE has changed over time and how it has been methodologically investigated in scholarly works. Although the initial contribution is academic, providing a framework for comprehending trends and gaps in VE studies, the findings are also pertinent to professionals in the urban development and construction sectors. These insights can facilitate the development and execution of vertical extension initiatives that are more well-informed and based on research, leading to evidence-based decision-making in practice. Consequently, the article recognizes its potential to enlighten practical applications while simultaneously situating itself within academic discourse.

The article's remaining content is organized as follows: The second section delineates the methodology utilized for the literature evaluation, specifying the data gathering and analysis procedures. The third section delineates the results and discussions pertaining to terminology, thematic, and methodological analyses, along with the potential implications of these findings for future study and practice. The study concludes with an overview of key findings and insights.

2. Methodology

This study implemented a systematic literature review in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to guarantee the transparency and reliability of the review procedure. The Scopus and Web of Science databases were chosen for their comprehensive coverage of high-impact, peer-reviewed publications and academic papers across several fields, ensuring the quality of the analytical material. The search strategy was formulated utilizing a mix of applicable keywords and Boolean operators to guarantee intensive retrieval of articles related to the study goals. To ensure that the literature study was comprehensive, no time or article-type restrictions were implemented; nonetheless, only papers written in English were examined. Figure 2 illustrates the employed search strategy. Following the removal of duplicates, and subsequent title, abstract, and full-text screening to evaluate the relevance of the available papers, a total of 119 articles were included in the final analysis. As mentioned, only non-English records and those not addressing VE (whether in general form or in specific aspects, like structural concerns) were excluded from the search results, with no other specific exclusion criteria.

A quantitative and qualitative content analysis approach (Newby 2014; Schreier 2014) has been used to perform the literature review. Content analysis is defined as "the study of content … by a reliance on a coding scheme based on a set of coding categories, a coder, and a body of text … to which the coder applies the coding scheme to quantify the frequency of occurrences of coding categories" (Franzosi 2008). To put it simply, content analysis can be used to identify the information contained in the textual material (Franzosi 2008). The coding

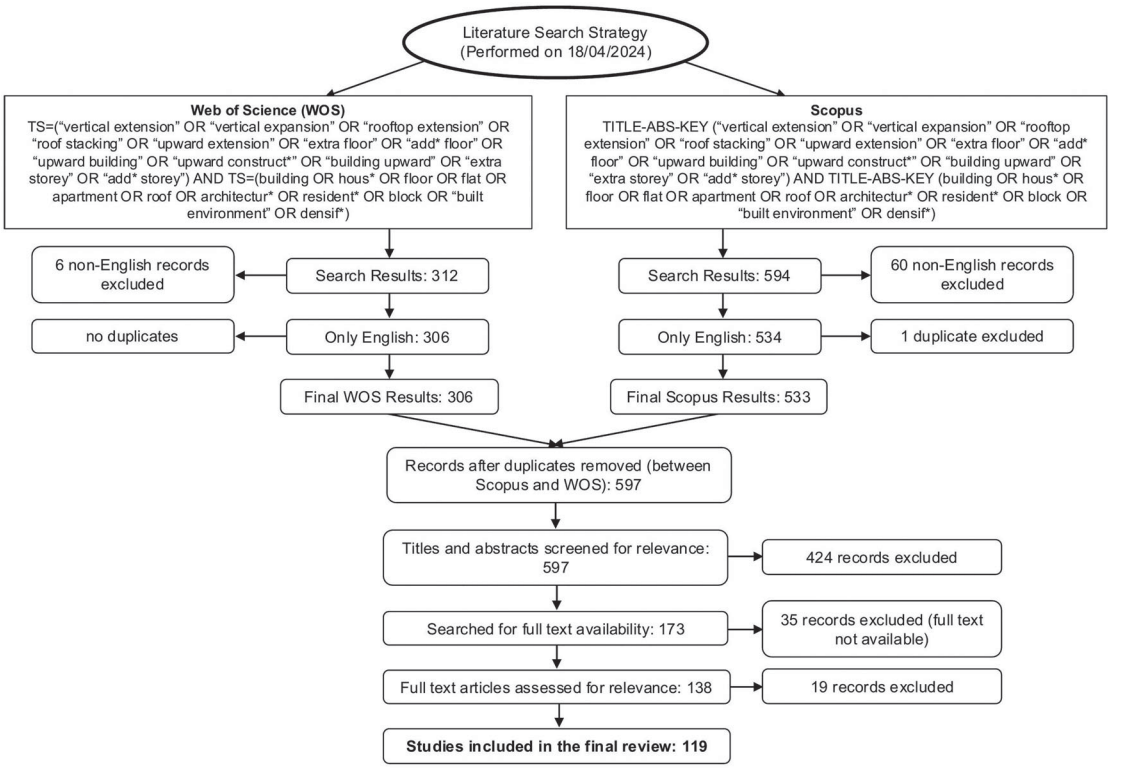

Figure 2. Literature search strategy flow chart.

technique in ATLAS.ti 9, a data extraction software tool that can be used for content evaluation, was used to do such (Hecker 2015). Several authors, including Caballero-Rico et al. (2022), Khodadad et al. (2024), and Moshood, Nawanir, and Mahmud (2022), have used ATLAS.ti for content analysis. Such practice stretches to literature reviews as well, as suggested by Kalpokaite and Radivojevic (2016) and Woods et al. (2016).

Following the identification of relevant articles, ATLAS.ti was used to import and analyze the full-text publications. The data-gathering procedure entailed an exhaustive full-text examination, concentrating on the extraction of essential material pertinent to the study's research aims. Using a manual coding process, all important and pertinent information from the articles was systematically coded. This inductive approach facilitated the emergence of categories and themes from the data during the course of the review.

The final data analysis was performed via ATLAS.ti, supplemented by Excel, GPT-4o, and Gephi, a prominent open-source programme for graph and network visualization (Gephi 2022), with the subsequent steps:

1. Code-to-Document Analysis: Following the coding process, a code-to-document analysis was conducted using ATLAS.ti. This was done to guarantee that each code was computed only once per document to avoid the over-representation of particular topics from highly detailed publications. This method facilitated a more equitable evaluation of the prevalence of various themes throughout the literature.
2. Co-occurrence Analysis: Co-occurrence analysis was conducted to investigate the links among the identified codes. The procedure entailed exporting co-occurrence data from ATLAS.ti into Excel, where additional quantitative analysis was conducted to examine the frequency and interrelations of themes throughout the articles. GPT-4o was also used for the co-occurrence analysis, with the outcomes validated by the authors through random selections.
3. Network Visualization: The data obtained from Excel was imported into Gephi to create visual representations of the co-occurrence associations. Gephi facilitated the creation of network graphs that visually depicted the links among topics of interest and research methods, offering insights into the structural linkages.

The methodological approach utilized in this study aligns closely with its primary purpose and research question, hence enhancing its academic rigour. The adoption of the PRISMA framework guarantees methodological transparency and reproducibility, which are essential characteristics of any systematic analysis. The study aims to clarify the evolution of discourse around VE and to analyze the definitions, topics, and methodology across various contexts, which is directly facilitated by the multi-phase, mixed-method approach. The integration of extensive database searches without temporal or article-type constraints and manual software-assisted coding utilizing ATLAS.ti, followed by co-occurrence and network analyses through Excel, GPT-4o, and Gephi, offers a thorough and expansive understanding of the methodological and thematic dimensions of VE research. This integrated methodology helps the identification of intricate patterns across time and space and permits a systematic analysis of the interrelatedness of concepts, so directly addressing the research aims and boosting the validity of the conclusions.

3. Results and discussion

3.1. Terms and definitions

When discussing the construction of additional floors on top of existing structures, a variety of terms are employed in different studies, and only a few of these investigations provide specific definitions of the terms used (Julistiono, Oldfield, and Cardellicchio 2023a). Table 1 describes all the different terms and definitions that we found from the studied literature along with examples of references where these are used. According to the examined literature, multiple terms are employed in research to describe a similar phenomenon, which means essentially "the addition of floors atop existing buildings," (Julistiono, Oldfield, and Cardellicchio 2023a). These include 'vertical extension' (e.g. (Gillott, Davison, and Densley Tingley 2022a; Norell, Stehn, and Engström 2020)), 'vertical expansion' (e.g. (Julistiono, Oldfield, and Cardellicchio 2023a, 2023b)), 'rooftop extension' (e.g. (Julistiono, Oldfield, and Cardellicchio 2023a, 2023b)), 'roof stacking' (e.g. (Amer et al. 2020; Amer and Attia 2019b)), 'upward extension' (e.g. (Julistiono, Oldfield, and Cardellicchio 2023a, 2023b)), 'additional floor/roof/elevation construction' (e.g. (Karjalainen et al. 2021a, 2021b)), and 'rooftop/airspace development' (e.g. (Gillott, Davison, and Densley Tingley 2022b)). Some sources also refer to it as 'adding floors to existing buildings', to bring the concept straightforward (Julistiono, Oldfield, and Cardellicchio 2023a). It is called 'aufstockung' in Germany (Floerke et al. 2014; Julistiono, Oldfield, and Cardellicchio 2023a), and Bojić et al. (2012) call it 'new-at-roof construction', a prevalent technique in Serbia over the past decade to acquire inexpensive residential space in desirable and expensive regions. Another term used in this field of research is 'vertical phasing', which cannot be considered as a synonym since it describes "the addition of five or more stories to an existing building" (Guma et al. 2009).

VE has been described in studies using a variety of terminologies thus far. Nevertheless, there are a number of drawbacks to using several terminologies to refer to roughly identical phenomena in research, such as decreased clarity, information fragmentation, and hampered teamwork. Different terminology makes it difficult to compile results and expand on what is already known, which leads to misunderstandings and inconsistencies in the literature (da Silva and Wheeler 2017). This further complicates communication among academics, practitioners, and policymakers, hindering multidisciplinary collaboration and constraining the actual implementation of research. Furthermore, the credibility of study findings is weakened as comparing data with various studies and performing a thorough literature review could be challenging. Standardizing terminology is crucial to ensure uniformity, improve cooperation, and facilitate knowledge synthesis in order to maximize impact and promote clearer, more effective research and practice (Khodadad, Aguilar-Barajas, and Khan 2023), indicating a focus for future research. In this regard, various types of VE could be considered or identified in terms of their structural, aesthetic, and regulatory variations, which would allow for more convenient application in future cases.

In this research, the term 'Vertical Extension' is used as we found it the most used term in academic research in this field. For this article, we refer to the definition by Norell, Stehn, and Engström (2020), who identify VE as "a vertical addition of a building volume that creates new or extends existing functions, both technical and operational".

3.2. Temporal evolution of VE research

The graphs below (Figure 3) show the number of publications published on VE research from 1991 to 2024, both annually and per half-decade. A significant rise in publishing began in 2017, culminating in a peak in 2019, which recorded the largest volume of papers published. This trend indicates a rising interest in VE, perhaps influenced by escalating urbanization and the demand for sustainable construction techniques. The number of publications has been continuously high in recent years, especially from 2020 onwards, indicating the continued relevance and significance of this field of study. The current growth of publications implies that the research area is maturing and becoming more integrated into modern building methods.

Several factors have contributed to the rise in research on VE constructions. Interest in VE projects is likely to be driven by urbanization trends and the increasing population density in cities, as constructing upwards provides an effective way to accommodate growing populations without extending urban sprawl (Julistiono, Oldfield, and Cardellicchio 2023a). Furthermore, regulatory modifications and updates, especially in building codes, are promoting vertical development in order to enhance land utilization, leading scholars to investigate the effects associated with these policies (Argenziano et al. 2021). Studies on the technical feasibility and efficacy of VE are also being stimulated by technological advancements, such as prefabrication and modular construction, which reduce construction costs and time (Dind, Lufkin, and Rey 2017). Moreover, increased concerns regarding the environment are prompting scholars to examine the ecological effects of VE, in accordance with international efforts aimed at minimizing carbon footprints and advancing sustainable construction practices, which are also supported by sustainability and green certification schemes (Sanei 2022; Sanei, Khodadad, and Calonge Reillo 2022a, 2022b, 2023).

3.3. Countries leading in vertical extension research

As seen in Figure 4, five countries are notable for generating the greatest number of papers on building VE. South Korea tops the sector with 19 publications, probably as a result of its dense urban population and scarcity of land (Mun, Lee, and Kim 2024), which necessitate creative architectural solutions like VE. Research in this field is further encouraged by the country's emphasis on earthquake-resistant buildings and cutting-edge construction technology (Faiella et al. 2023). For example, in order to increase the safety of the urban environment, Cheng-Can and Jin-Tae (2017) examined load distribution in vertically expanded structures, which is essential for structural safety in densely populated cities like Seoul, leading to improved urban environment safety (Khodadad and Sanei 2016). South Korea is followed by Italy and the United States, each of which has 11 publications. Italy is motivated by the necessity of integrating contemporary extensions with historic structures, particularly in the preservation of cultural sites and the optimization of

Table 1. VE-related terms and definitions.

Term	Definition	Reference
Vertical Extension	• "A vertical addition of a building volume that creates new or extends existing functions, both technical and operational". • "(VE) can be considered complex systems since at least two parts interact dynamically to function as a whole and the parts are interconnected". • "A vertical addition of a host building that creates new or extends existing functions, both technical and operational", that "can be related to retrofitting to add functions to a host building"	.(Norell, Stehn, and Engström 2020)
	"The adaptation of an existing building through the addition of new storeys, realizing the embodied carbon savings of building reuse whilst also generating new useable floorspace".	(Gillott, Davison, and Densley Tingley 2022a)
	"A structure that is constructed upon the top floor-space – generally the roof – of an existing building, adding one or more storeys" that is a "re densification solution in the urban environment".	(Julistiono, Oldfield, and Cardellicchio 2023a), based on the definition in (Floerke et al. 2014)
Roof Stacking	"The methods of bearing additional loads on the existing building from one hand, and the methods of assembling additional roofs from the other hand".	(Amer and Attia 2019b)
	"The added structure over the rooftop of an existing building to create one or more stories of living spaces".	(Amer et al. 2020)
Additional Floor Construction; Additional Roof Construction; Additional Elevation Construction	"(Changing) the roof shape of the building … (and increasing) the height of the building and the number of floors".	(Karjalainen et al. 2021a, 2021b)
Vertical Extension; Rooftop Development; Airspace Development	"The construction of new storeys above existing buildings", which is "most often completed as part of a wider retrofit, or specifically with minimal impact upon the existing structure".	(Gillott, Davison, and Densley Tingley 2022b)
Vertical Extension; Vertical Expansion; Rooftop Extension; Roof Stacking; Upward Extension; Aufstockung; 'Adding floors to existing buildings'	"The additional floor(s) atop existing buildings".	(Julistiono, Oldfield, and Cardellicchio 2023a)
Vertical Extension; Aufstockung; Vertical Expansion; Roof Stacking; Rooftop Extension; Upward Extension	"Building additional stories over an existing building".	(Julistiono, Oldfield, and Cardellicchio 2023b)
Vertical Phasing (not identical)	• "Constructing first a shorter building and then adding significant expansion later by increasing the building's height". • "The addition of five or more stories to an existing building".	(Guma et al. 2009)

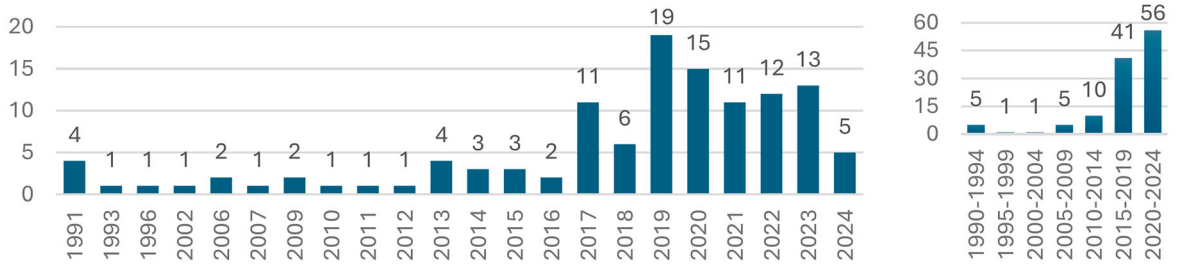

Figure 3. Number of articles published on VE research per year and half-decade.

urban space, due to its rich architectural heritage. As an example, through research such as (Esposito, Faiella, and Mele 2024), the country investigates structural advances for historic buildings. In contrast, the United States is seeing a rise in interest in VE because of its large urban centres (e.g. New York City) and the country's increasing focus on energy-efficient construction techniques and sustainable development. Articles like the work of Dutta et al. (2009) highlight environmental sustainability and seismic safety in the United States.

The subsequent countries are Belgium and China, each with ten publications. Belgium's emphasis on VE as an approach to energy-efficient urban development, particularly in dense European cities, is a result of its leadership in sustainable energy-efficient construction. This emphasis is evident in Belgium's work, including the work of Amer et al. (2019a). In China, VE is a critical research area as well, as the country is under intense pressure to maximize land use in main cities due to rapid urbanization and large-scale construction projects. For instance, reflecting the country's rapid urbanization and increasing need for VE, Guo et al. (2012) focused on structural analysis in buildings. A noticeable gap in publications can be seen after the top five countries. Sweden, for example, follows Belgium and China with five articles that mostly focus on design and planning in VE projects. Reflecting Sweden's emphasis on sustainable urban planning, Sundling (2019) examined case projects to identify the enabling success variables for VE adoption.

As many countries have fewer than three publications, the distribution of the publications in various global regions, including sub-regional divisions for areas with more publications, is shown in Figure 5. The regional representation illustrates a complementary detailed view of (sub)regional trends and gaps. As seen, the global distribution of publications on vertical building expansions is disparate, with significant concentrations in

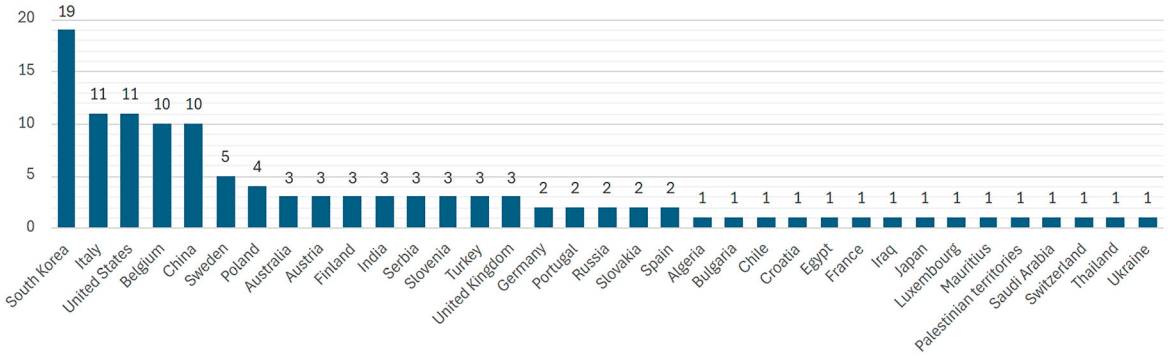

Figure 4. Countries producing the most publications on the VE of buildings.

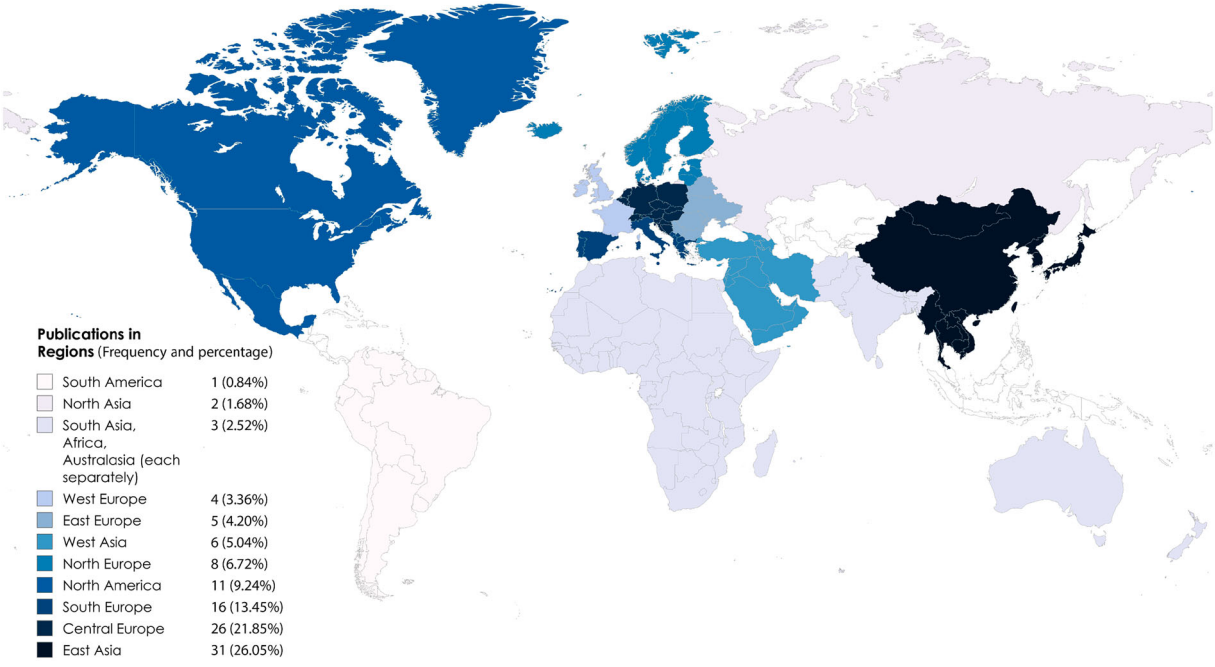

Figure 5. Distribution of publications on the VE of buildings in various regions.

East Asia, Central Europe, and Southern Europe, which comprise the highest number of publications (31, 26, and 16 articles, respectively). These areas typically possess dense urban settings, established legal frameworks, and sophisticated infrastructure, all of which promote and facilitate vertical development. In East Asia, land shortages and stringent zoning regulations render vertical construction a strategic approach, whereas in Europe, the preservation of old urban centres frequently promotes vertical repurposing and adaptation. These structural and policy-oriented elements may elucidate the elevated academic production in these regions.

In contrast, limited publication activity is observed in regions such as South America, North Asia, South Asia, Africa, and Australasia, with each producing one to three papers. The diminished outputs may arise from several problems, such as economic limitations, inadequate regulatory enforcement, insufficient infrastructure, and climatic or seismic issues that hinder vertical building. According to our results, Central and Southeast Asia, as well as Central America, lack documented publications (our study limitations should be considered when interpreting), underscoring evident research gaps. These underrepresented regions provide chances for future research customized to local circumstances, yielding useful insights into how vertical expansions can meet housing, sustainability, and urban resilience requirements across many global contexts.

3.4. Topics of interest in VE research

Figure 6 illustrates that the investigation of VE within existing buildings has been significantly centred on a variety of critical areas, with certain key topics emerging as the most extensively researched. The complete list of topics is available in Appendix A. The most frequently encountered topic is 'Structural analysis/reinforcement techniques', which has been examined in 50 articles. For example, Shala and Bleiziffer (2024) examined the seismic performance of reinforced concrete frames in extended constructions, stressing the impacts of structural joints on structural integrity. In a similar vein, Esposito, Faiella, and Mele (2024)

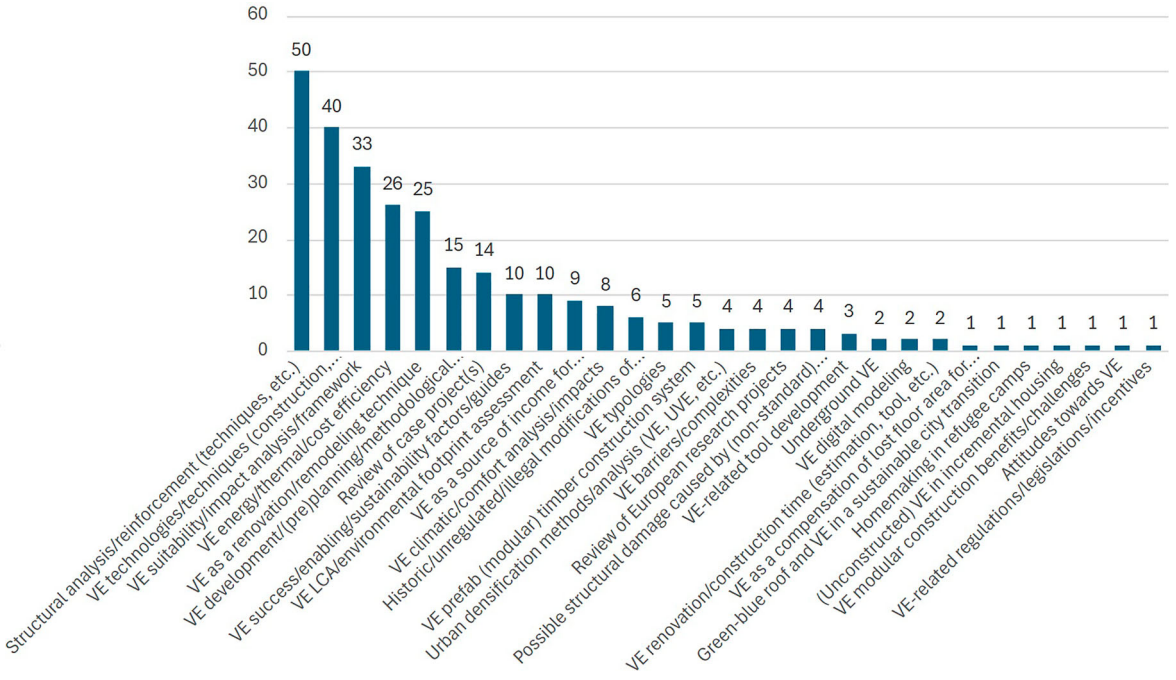

Figure 6. Topics investigated within VE research.

investigated intermediate-story structural isolation techniques in vertically expanded structures and evaluated their effects on the stability of the structure. 'VE technologies/techniques (construction, innovative structural elements, design, etc.)' is the second most often investigated topic, with 40 publications on the subject. For instance, Sundling (2019) presented novel methodologies and structural components employed in VE projects to improve design. Furthermore, three renovation systems for mixed-use buildings, low-rise residential structures, and apartments were presented by Amoruso and Schuetze (2022), using hybrid timber technologies.

'VE suitability/impact analysis/framework', the third topic, is examined in 33 papers. For instance, a system for evaluating VE projects using environmental impact measurements and digital modelling was offered in the work of Daher, Kubicki, and Marvuglia (2023). Additionally, Gillott, Davison, and Densley Tingley (2022b) developed a multi-scalar framework to evaluate the potential of VE in providing housing. The 26 publications that study 'VE energy/thermal/cost efficiency', the next most frequent topic of interest, include research such as the work of Dind, Lufkin, and Rey (2018), which evaluated the lifecycle and energy efficiency of modular wood construction for VE. Likewise, Amer and Attia (2019a) investigated how energy efficiency and cost are balanced in zero-energy building projects. 'VE as a renovation/remodeling technique' is the fifth most popular topic of interest, with 25 articles discussing the application of VE as an urban regeneration strategy. For example, Soikkeli (2016) assessed the addition of floors in historic European structures as a tool for urban regeneration, while Bertolazzi et al. (2019) suggested a methodological framework for incorporating VE into current rehabilitation projects, with a focus on structural strengthening.

Topics with low frequencies (one or two) indicate areas that are less commonly discussed but still hold importance in specific contexts or emerging trends and should be discussed in future research. Examples are 'Underground VE', 'VE-related regulations/legislations/incentives', and 'Attitudes towards VE'. Evidenced by the presence of a variety of topics in VE research, researchers seem not to be exclusively concerned with the technical aspects but also interested in other dimensions of VE, like the economic and social implications. This holistic strategy, which should be enhanced in future research, is crucial for guaranteeing that vertical expansions are both viable and advantageous to communities considering socioeconomic and environmental domains.

3.5. Methods used in VE research

In the investigation of VE, many strategies have been employed, resulting in the emergence of several notable methods (Figure 7). A list of all methods can be found in Appendix B. The predominant methodology utilized is the 'Case study–reference model–experimental prototype–illustrative example', employed across 86 papers. For example, Wang and Han (2021) analyzed the impact of preloaded micro piles on the foundation via experimental testing, and Amoruso and Schuetze (2022) introduced three renovation strategies utilizing hybrid timber technology for three prevalent building types in South Korea. 'Structural modeling/analysis', is the second most popular approach, used in 52 publications, including the work of Esposito, Faiella, and Mele (2024), which involved designing and evaluating intermediate story isolation for VE projects. Likewise, Cheng-Can and Jin-Tae (2017) used structural modelling tools to evaluate the stability of structures undergoing VE.

'Energy/thermal/climatic/environmental simulation/calculation', is the third important method that has been utilized in 23 studies, frequently to evaluate the energy and environmental effects of VE projects. For example, Vuckovic et al. (2019)

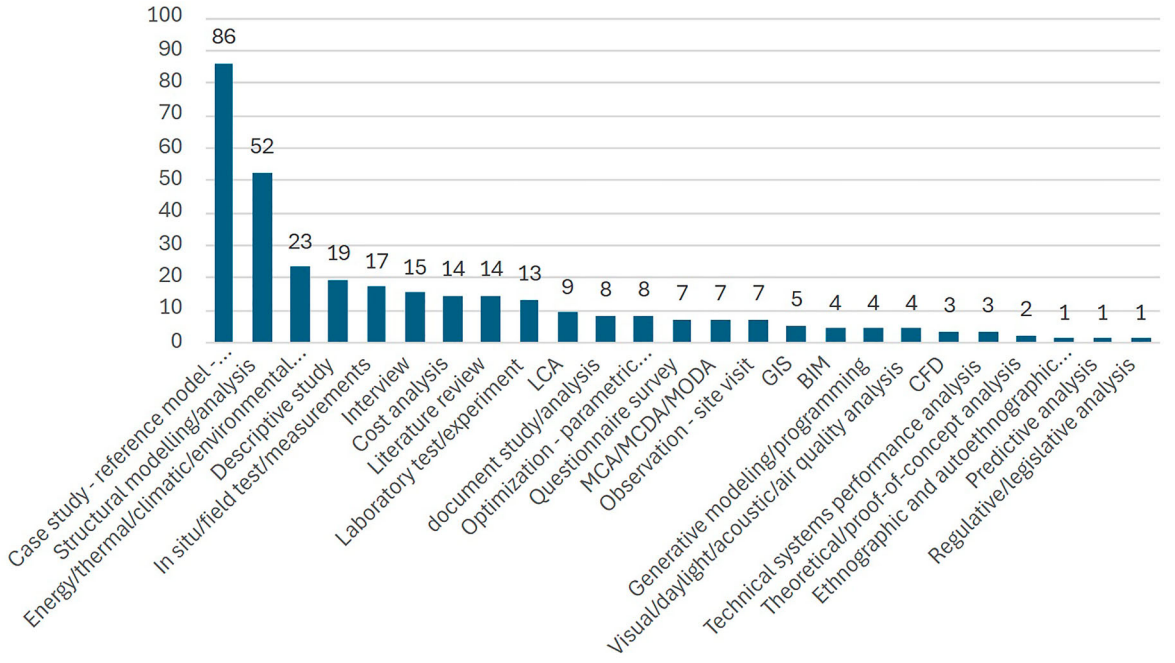

Figure 7. Methodological approaches used in VE research.

assessed the potential of VE and urban densification to alleviate heat island effects. Furthermore, Dind, Lufkin, and Rey (2018) assessed the sustainability of modular timber building systems in VE projects using environmental models. The subsequent greatest rate (18 articles) pertains to the methodological approach of 'Descriptive studies'. For instance, Soikkeli (2016) provided a descriptive examination of European projects that add floors to existing structures, and Cherkas and Rimshin (2017) explained how composite materials might improve structural reinforcement in VE projects. Furthermore, actual data from practical applications is provided by 'In situ/field test/measurements', which is used in 17 publications. For example, Choi, Kim, and Cho (2020) discussed measuring the stiffness of piles in the field to support extra floors in buildings, and Jaśniok and Jaśniok (2020) used in-situ tests to find structural problems in concrete buildings that have been extended vertically.

Methodological approaches with lower frequencies, such as 'Regulative/legislative analysis', 'Predictive analysis (MCS[1], etc.)', and 'Theoretical/proof-of-concept analysis', represent emerging areas or less explored methods within the field, potentially highlighting opportunities for further research and discussion. Overall, the methodological approaches utilized in VE research provide a wide spectrum of analytical tools, from theoretical modelling to real-world testing, highlighting the field's comprehensiveness.

3.6. Co-occurrence analysis

Intricate relationships among various topics and methodologies within the literature are revealed by the network graphs in Figure 8, which provide an extensive overview of the research landscape surrounding building VE. The most frequently examined topics or methods are represented by the larger nodes in the figures. Likewise, a higher frequency of co-occurrence in the literature is indicated by the thicker lines connecting nodes. The analyzed pairings of methodologies and topics show how theoretical, practical, and environmental factors are linked in the area of VE research, emphasizing a multifaceted approach to urban development.

3.6.1. Research method pairs

As shown in Figure 8 (left), the most common method pair in VE studies is 'Case study–reference model–experimental prototype–illustrative example' and 'Structural modeling/analysis', which appear together in 46 papers. This combination highlights how crucial it is to use structural models in real-world practical case studies in order to verify theoretical conclusions. A case in point is the work of Cheng-Can and Jin-Tae (2017), which used structural modelling within cases to examine the effects of additional floors on buildings' load-bearing capacities. In the same vein, Esposito, Faiella, and Mele (2024) employed both structural models and case studies to assess the effectiveness of isolation methods in multi-story buildings. 'Case study–reference model–experimental prototype–illustrative example' and 'Energy/thermal/climatic/environmental simulation/calculation' shape the second most prevalent combination, represented by 17 articles. In real-world VE applications, this combination is crucial for assessing environmental effects and energy efficiency. For example, Sundling, Blomsterberg, and Landin (2019) used both approaches to show how VE might render renovation projects more energy-efficient. The pairing of 'Case study–reference model–experimental prototype–illustrative example' and 'In situ/field test/measurements' is also common and appears in 17 articles. Projects that need field measurements to empirically validate the design and structural assumptions may benefit from this combination. For example, Kim, Kim, and Jeong (2019) assessed the axial stiffness of piles in structures undergoing VE using numerical models validated by field measurements.

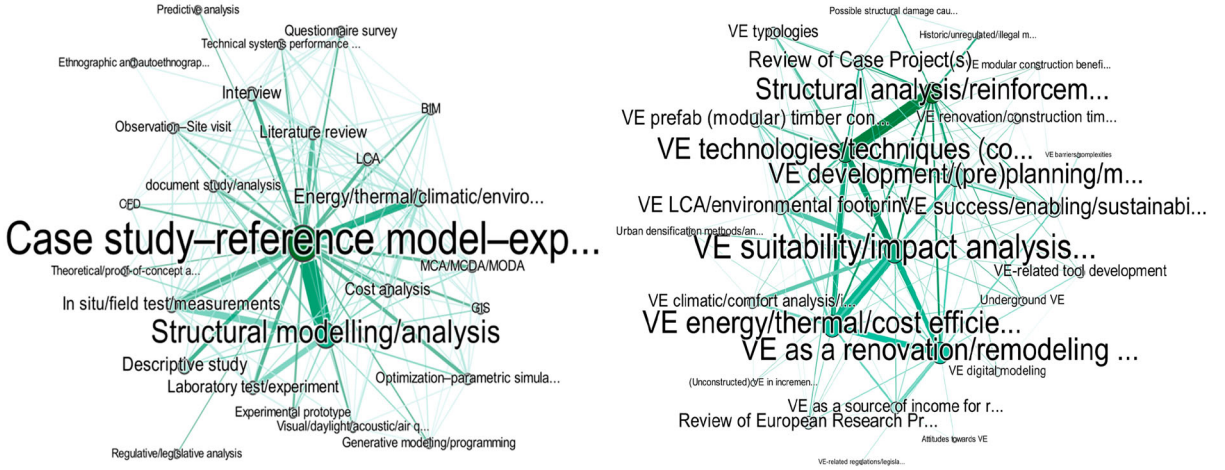

Figure 8. Network analysis of VE research landscape: (left) topics of interest; (right) methodological approaches.

It can be seen that the current literature is heavily biased toward technical and performance-based approaches, such as structural modelling, environmental simulation, and reference model/prototype analysis. In contrast, human-centred, regulatory, and theoretical analyses are underexplored and isolated. The absence of interdisciplinary integration restricts an in-depth understanding of the broader implications of VE. It is important to note that technical methods are rarely used in conjunction with ethnographic research, legislative analysis, and predictive modelling, which suggests a fragmented research landscape. In order to reflect the intricate, real-world conditions under which VE initiatives are developed, future research should integrate technical analyses with social, legal, and policy-oriented approaches to address these gaps. The establishment of theoretical frameworks that connect these disparate approaches would progress the discipline even more by providing a more comprehensive and strategically sound basis for both scholarly research and real-world implementation.

3.6.2. Topic pairs

According to Figure 8 (right), 'Structural analysis/reinforcement techniques' and 'VE technologies/techniques (construction, innovative structural elements, design, etc.)' are the most common topic pairs, appearing in 25 publications. This combination emphasizes the necessity of combining structural reinforcement investigation with innovative construction technologies to guarantee the stability of structures that are expanded vertically. For example, Wang et al. (2019) implemented a novel micro-pile design known as the waveform micro-pile to improve the foundation's load-bearing capacity, and Faiella et al. (2023) evaluated the efficacy of isolated VE in masonry structures as a nonconventional Tuned Mass Damper to lessen seismic demand and risk. This common combination of topics demonstrates a tendency towards adopting advanced building techniques in conjunction with structural reinforcements to deal with urban densification concerns.

'VE energy/thermal/cost efficiency' and 'VE suitability/impact analysis/framework' are the second most frequently encountered topic pairings, with 22 articles addressing them. In order to assess the economic and environmental feasibility of VE initiatives, this combination is crucial. For instance, Amer and Attia (2019a) investigated the cost and energy effectiveness of light-frame structures, whereas Wijnants, Allacker, and de Troyer (2017) analyzed the environmental and economic impacts of "open-renovation-systems" in residential VE. 'VE suitability/impact analysis/framework' and 'VE technologies/techniques (construction, innovative structural elements, design, etc.)' are the third most frequently occurring pair, appearing in 12 publications. The necessity of evaluating the feasibility of inventive VE techniques within practical frameworks is emphasized by this pairing. As examples, Seo, Lee, and Won (2020) investigated the financial effects of three VE techniques for the basement floor of existing structures, while Mendonça, Macieira, and Guedes (2020) provided a thorough study of the thermal efficiency of the six rooftop expansions, contrasting architectural membranes and traditional construction techniques. The prevalence of these combinations of topics underscores the greater need to assess new VE technologies for their practical applicability.

Several emergent themes may be detected, including 'Sustainability and Technology' and 'Community and Social Considerations'. The topics of 'VE-related tool development' and 'VE LCA[2]/environmental footprint' indicate an increasing focus on sustainability and the application of advanced technology in vertical construction. This tendency may be impacted by the increasing prevalence of digital tools like Building Information Modeling (BIM), which make vertical expansion planning and analysis more effective. Furthermore, the inclusion of topics like 'attitudes towards VE' reflects a move towards a broad comprehension of the larger VE implications. Scholars may investigate the ways in which these developments impact nearby communities, examining both the possible advantages – like providing a possible revenue stream for building owners – and the drawbacks – like altering the character of the neighbourhood. It is very likely that these new subjects will be further explored in the near future.

3.6.3. Publication year and topics of interest

As previously stated, the study of VE has changed dramatically throughout time, with significant changes in approach and concentration. Figure 9 shows clear trends in the distribution of different topics throughout time. Notably, there is a rise in certain topics in particular periods. Early 1990s papers, such as the work

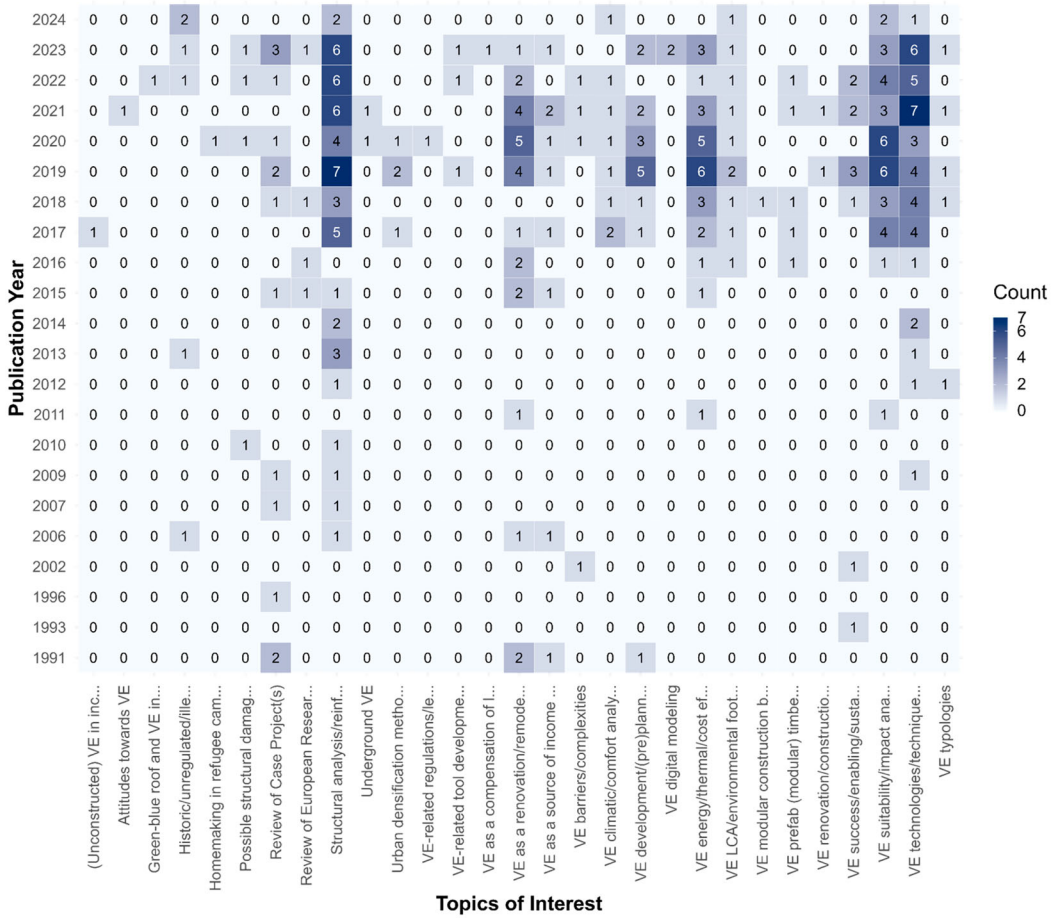

Figure 9. Heatmap of co-occurrence between topics of interest and publication years.

of Thornton, Hungspruke, and DeScenza (1991), examined the fundamental viability of adding floors to existing buildings and cases, indicating a growing interest in VE, as urban space became more limited. By the mid-2000s, authors began to perform structural analysis and assess the reinforcement techniques. For instance, Kahraman, Saatci, and Misir (2006) examined the issues associated with vertical expansions, emphasizing the structural risks that such modifications entail. In the 2010s, energy efficiency and sustainability became increasingly important, leading to several publications in areas like 'VE energy/thermal/cost efficiency' and 'VE suitability/impact analysis/framework'. One example of this is the work of Amer and Attia (2019a), which concentrated on incorporating VE into green construction techniques. Publications on these topics increased dramatically after 2016, with authors like Sundling (2019) offering frameworks to facilitate effective VE initiatives.

In recent years, 'Structural analysis/reinforcement techniques' and 'VE technologies/techniques' have attracted the greatest attention. In addition, recent articles like the work of Daher, Kubicki, and Marvuglia (2023), which incorporate environmental impact analysis and LCA into VE design, further demonstrate the development of modern analytical techniques in VE research, indicating the field's continued complexity. Comparable patterns may also be seen in the emergence of some new subjects over time, such as those pertaining to VE-related tools and prefab construction systems, which demonstrate the evolution of the field of study. This progression over time indicates that research has expanded from straightforward feasibility studies to intricate, technologically advanced, and sustainability-focused analysis, pointing to the possibility of even more such investigations in the future.

3.6.4. *Countries and topics of interest*

As seen in Figure 10, research on certain topics is more prevalent in certain countries, indicating the impact of local socioeconomic, environmental, and regulatory issues. For instance, the prevalence of the subject 'Review of case project(s)' in the US indicates a research culture that prioritizes empirical, practice-oriented learning derived from real-world instances. This may arise from the United States' vast history of urban reconstruction, varied architectural inventory, and the institutional focus on case-based education in engineering fields. Multiple countries, such as Belgium, South Korea, and Italy, exhibit a varied strategy, addressing a broad spectrum of VE-related subjects, like structural reinforcement, suitability and impact analysis, technological aspects, and environmental modelling. This extensive research agenda may indicate national strategies that encourage interdisciplinary collaboration, investment in smart city projects, or a more intricate urban development landscape necessitating numerous solutions.

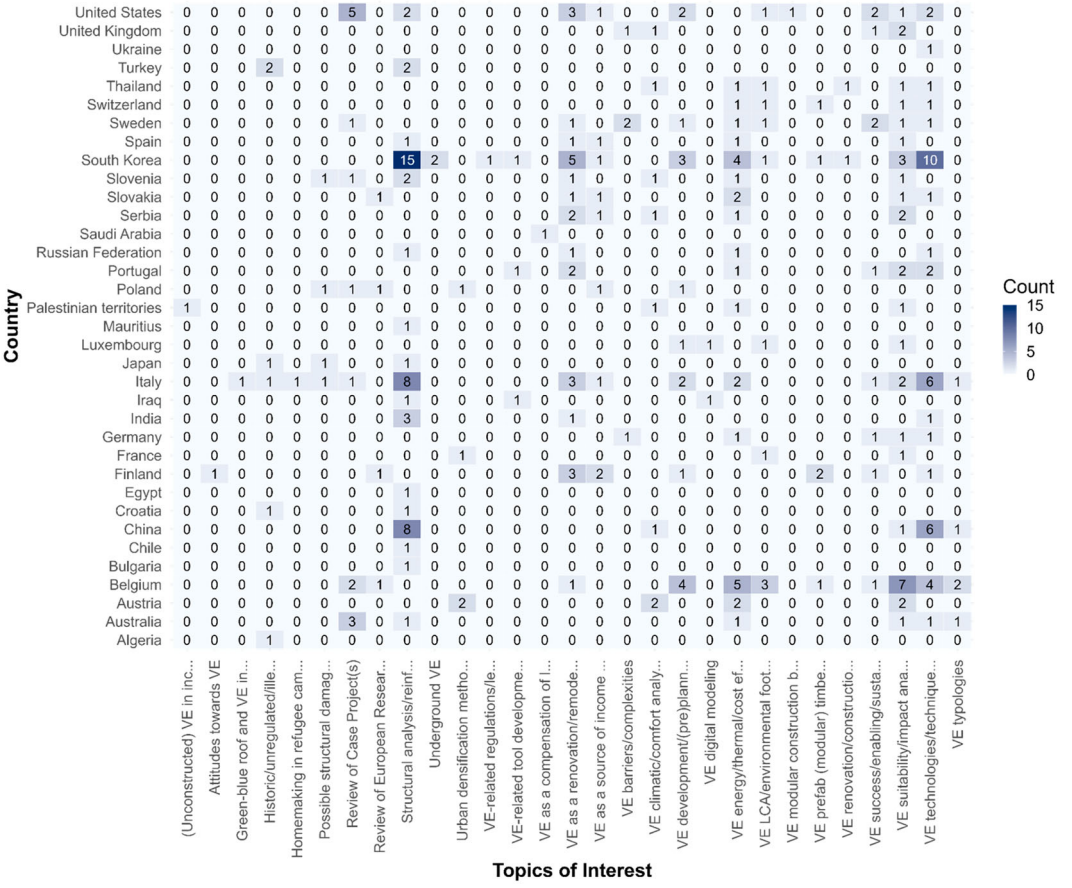

Figure 10. Heatmap of co-occurrence between topics of interest and publication countries.

Conversely, countries like India and Turkey concentrate their research on fewer subjects, such as 'Structural analysis/reinforcement', underscoring a more focused, application-oriented approach. This specialty likely stems from context-specific requirements, such as aging infrastructure, seismic susceptibility, or changing safety regulations. Constrained research funds or institutional capacity may also prompt an emphasis on the most immediately impacting or technically challenging facets of VE. Overall, the heatmap illustrates how regional context – including infrastructural conditions, building typologies, legislation, and climatic risks – can shape national research goals. Consequently, nations may tailor their academic emphasis and launch new research lines according to regional knowledge gaps, practical limitations, or nascent technologies, thus making distinctive contributions to the global dialogue on vertical extension methods.

3.6.5. Topics of interest and methods

There are many different topic-method co-occurrences in the academic literature relating to VE, as shown in Figure 11. The practical aspect of VE research is evident in the point that 'Case studies' are the most commonly employed research approach, linked with almost all important topics. The majority of research seeks to validate theoretical frameworks or apply them in practical contexts; this is especially true in fields like structural analysis and environmental footprint evaluations.

An explanation of a few important topic-method pairings that are highlighted in the heatmap are as follows:

— 'Structural Analysis/Reinforcement Techniques' with 'Case study–reference model–experimental prototype–illustrative example'

There are few pairings as common as this one. Research on structural analysis and reinforcement frequently use case study approaches. This includes methods for either reinforcing or modifying structures to allow vertical expansions. This points to the importance of examining technical issues with actual case studies and real-world instances.

— 'VE LCA/Environmental Footprint' with 'Case study–reference model–experimental prototype–illustrative example'

Research on the effects of vertical expansions on the environment and life cycle assessments frequently makes use of case studies and reference models. This combination implies that theoretical modelling is used to enhance the exploration of environmental issues through applied cases.

— 'VE Suitability/Impact Analysis/Framework' with 'Energy/Thermal/Climatic/ Environmental Simulation/Calculation'

The use of numerical analysis or simulations to examine different energy- and environment-related factors is common in articles examining impact or suitability frameworks and analyses. These analytical methodologies enable scientists to quantify and assess the qualitative dimensions of VE, resulting in

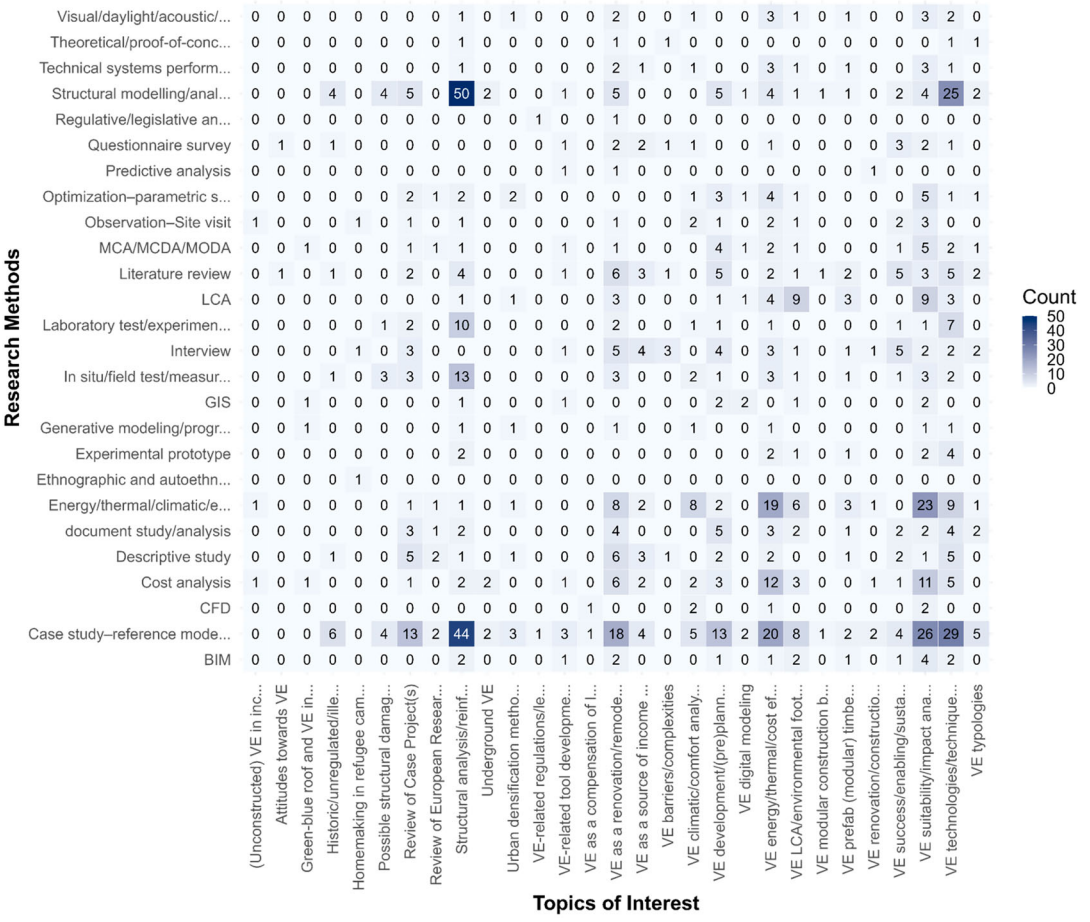

Figure 11. Heatmap of co-occurrence between topics of interest and research methods.

guidelines and frameworks for practical applications. The ability to develop practical frameworks and practices is directly proportional to the accuracy of our information analysis tools and methodologies. The more accurate the tools and techniques we employ for analysis, the more practical the frameworks and practices may be.

In general, the study landscape of VE predominantly favours issues associated with case studies, structural analysis, and energy/climate-linked approaches, especially in technically oriented studies such as structural behaviors, suitability, and technologies. The heat map indicates significant potential for establishing more method-topic connections in future research, particularly qualitative research methodologies in the exploration of socioeconomic topics of interest.

4. Conclusions

This review presents the current state of VE research based on a comprehensive review of 119 research studies. Our main research question was: What are the key definitions, thematic emphasis, and methodological approaches utilized in VE studies, and how are they assessed across various temporal and spatial settings? The investigation of VE terminology demonstrates the field's fragmentation, since various names are used interchangeably to refer to comparable processes, resulting in confusion and conflicting results among research. Analyzing the temporal evolution of publications indicates that research on VE has significantly increased since 2017. This reveals that VE is becoming more and more relevant as an alternative for urban densification. The pressing need for sustainable urban development in rapidly growing cities is probably what is behind this increased trend. South Korea, Italy, and the US are at the forefront of VE research, in which VE research and implementation have been driven by urban density, legal structures, and technical breakthroughs. Increasing the scope of study to under-represented areas will yield a more thorough picture of VE practices worldwide.

The primary topics of interest in VE studies underscore the predominance of structural evaluation and reinforcing methods, technologies and techniques associated with VE, as well as the suitability and impact assessments and considerations. The combination of modern construction practices with sustainability aims is a prevalent theme, illustrating the sector's multidimensional and comprehensive perspective. The relationship between structural analysis and VE technologies is further highlighted by the co-occurrence analysis of research topics, underscoring the significance of combining cutting-edge techniques with reliable construction designs. Our research identified knowledge gaps on topics, including legal frameworks and public perceptions, that are crucial for a thorough comprehension of VE implications but are still seldom studied. While new themes like 'Sustainability and Technology' and 'Community and Social Considerations' are becoming more popular, more research should be carried out in these areas in the

future. Guiding responsible and inclusive vertical development will need extending research beyond/beside technical issues to incorporate regulatory, environmental, and societal dimensions.

The analyzed literature demonstrates a strong emphasis on empirical verification and real-world implementation, as evidenced by the dominant use of case studies and structural modelling in VE research. The necessity for further qualitative research to back up VE procedures is highlighted by this methodological preference. Furthermore, the intimate connection between case studies and structural modelling – which are commonly used to evaluate the viability and safety of VE projects – is reflected in research method pairings. In contrast, human-centred, regulatory, and theoretical analyses are underexplored and isolated. It is important to note that technical methods are infrequently combined with legislative analysis, ethnographic research, and predictive modeling, which suggests more future interdisciplinary approaches. Future studies should bridge the gaps by combining technical analyses with social, legal, and policy-oriented approaches to reflect the complex, real-world circumstances in which VE initiatives are formed.

Topic-method pairs highlight the practical character of VE research by demonstrating how structural reinforcing methods and energy efficiency and environmental evaluations are frequently investigated through case studies and reference models. The analysis highlights significant potential for establishing more method-topic connections in future research, particularly qualitative research methodologies in the exploration of socioeconomic topics of interest. A trend towards more sophisticated, sustainability-focused research is shown by the investigation of topic evolution over time, which might be continued in future studies. Finally, according to the analysis of regional settings, VE research is more concentrated in a small number of top countries, with limited input from areas that can use VE alternatives. Expanding VE studies to more varied urban contexts could be the goal of future studies in order to address this imbalance.

In general, we believe our study offered a fresh viewpoint by elucidating the evolution of discourse around VE and delivering a comprehensive examination of the methodology utilized in existing investigations, which, to our knowledge, has not been previously applied in this field of study. The findings offer significant insights to researchers and academics, presenting a thorough comprehension of the field's current status and potential areas for development. This review, likewise, provides practical implications for architects, engineers, and policymakers. Initially, it facilitates more informed decision-making by delineating methodological and thematic tendencies, assisting professionals in aligning their work with established research. Second, the findings underscore the significance of interdisciplinary methods, promoting collaboration among technological, socioeconomic, and policy sectors to develop more comprehensive and robust VE strategies. Third, the review highlights an important gap in regulatory and legislative analysis, indicating the necessity for policymakers to establish revised frameworks and incentives that promote VE in urban settings. Finally, the increasing focus on public perceptions and societal implications compels designers and engineers to prioritize user-centred, context-sensitive solutions that promote community acceptability.

Nevertheless, this study is subject to several limitations, as is the case with any systematic literature review. Initially, the review is restricted by its dependence on articles indexed in Scopus and Web of Science, which, despite their comprehensiveness, might exclude pertinent studies from other databases or grey literature that are not available through these search engines. Second, the review exclusively encompasses publications in English, which may result in the exclusion of significant contributions published in other languages, particularly from regions where VE research may be under-represented in English-language journals. Furthermore, despite all efforts to implement consistent coding practices, the classification of themes and methodologies through content analysis is susceptible to interpretive bias.

The necessity for comprehensive research into critical non-technical factors affecting the successful delivery of VE, such as social acceptance, implementation costs, and economic incentives, is emphasized and acknowledged. While these areas were implicitly included in our review, our focus was not explicitly intended to analyze them in depth. Nevertheless, these elements are essential in assessing the viability and scalability of VE projects, especially in competitive real estate markets where financial feasibility and stakeholder engagement are critical. Therefore, to accurately represent the complexity of real-world VE applications, future research would benefit from interdisciplinary research including more economic and social factors. Thoroughly examining these concerns may yield significant insights for lawmakers, developers, and urban planners aiming to execute VE policies that are both technically robust and socioeconomically viable. This can substantially enhance the development of more comprehensive and contextually aware approaches for VE research and implementation.

Notes

1. Monte Carlo Simulation.
2. Life Cycle Assessment.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [MS], upon reasonable request.

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