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Existing industrial buildings – A review on multidisciplinary research trends and retrofit solutions

Neri Banti

Department of Civil and Environmental Engineering, University of Florence, S. Marta Street 50139 Florence, Italy

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ABSTRACT

In order to meet the international goals for a sustainable development, it is mandatory to implement energy saving solutions on existing buildings and industrial ones should be also addressed since industry related consumption covers approximately one third of the global energy demand. Industrial facilities are usually characterized by low overall quality standards and performance levels, largely influenced by their old age and architectural/technological, energy, and structural issues. The paper aims at outlining the current state of the research on manufacturing facilities, focusing on their energy efficiency and the related redevelopment solutions. The PRISMA methodology was adopted in the initial stages, coupled with a computer-aided bibliometric review tool: globally, 203 scientific papers retrieved on Web Of Science and ScienceDirect databases were analysed. Three main areas of interest were pointed out referring to structural and seismic behaviour, building envelope and systems performance, and energy-related issues. The analysis conducted revealed a significant gap in the literature concerning integrated retrofit solutions for industrial facilities and the review serves as a robust knowledge base for the development of comprehensive redevelopment guidelines for this peculiar building stock.

1. Introduction

Nowadays industry is responsible for about one third of the global total final energy consumption [1] and a series of concrete actions to reduce the environmental impact of this sector should be adopted to meet the ambitious goals set by different international institutions. European Union aims at achieving a climate-neutral economy within 2050 in line with the Paris Agreement [2] and sustainable industrialization is addressed by the United Nations as a clear goal among the ones mandatory for a sustainable development to be met by 2030 [3]. In recent years, a growing awareness of sustainability-related concerns in the business sector has been driven by regulatory pressures, the adoption of eco-friendly policies, and the increased energy costs, particularly influenced by global geopolitical factors. Recently the European Union strengthened its prescriptions following the introduction of the new Energy Performance of Buildings Directive [4] and promoted a series of renovation initiatives on existing buildings within the framework of the new European Green Deal [5]. The 80 % of the existing European building stock is expected to be still used within 2050 and retrofit measures should be definitely deployed on a wide scale to ensure the sustainability of the built environment [6]. In the last decade, a proliferation of researches addressing large set of facilities can be retraced but they mainly focus on buildings with intended uses different from the industrial ones, primarily addressing the residential [7,8] or educational-religious ones [9]. Only a few large scale and systematic investigations on this field can be retraced but still suffering from the lack of adequate scalability relating to specific construction technologies and geographical scenarios [10]. Extensive surveys of large portions of the Italian territory [11–15] pointed

E-mail address: neri.banti@unifi.it.

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out a series of deficiencies in aging industrial facilities. Originally built following post-World War II economic growth demands, these buildings lack compliance with effective standards for energy performance and environmental requirements. For cost-effectiveness and efficiency, precast concrete systems were selected as the primary construction solution. However, a lack of attention to appropriate technologies during the design stages, combined with insufficient maintenance, has resulted in progressive and widespread deterioration of building properties. Furthermore, the presence of asbestos-containing roofing components poses health and environmental risks. Structural deficiencies were dramatically highlighted by recent seismic events in the Mediterranean region, resulting in localized failures and collapses of load-bearing structures. The visual aesthetics of these manufacturing buildings fall below contemporary standards, contributing to a nondescript and low-quality built environment. For developing countries, the implementation of energy efficiency measures in industrial buildings should align with the transition to an energy mix including renewable sources. Given these challenges, further research on the integrated redevelopment of manufacturing buildings is essential.

After conducting a preliminary literature review, it has come to the author's attention that there is currently a lack of comprehensive, multidisciplinary and systematic state-of-the-art reviews on industrial buildings in the scientific literature. The presented research aims to address this knowledge gap providing an extensive review of the currently available studies focusing on the following aspects:

- identification of the current trends in scientific research about industrial buildings;
- assessment of the most discussed research fields related to the target facilities;
- detailed analysis of redevelopment strategies and solutions applied in industrial facilities.

2. Methodology

To ensure a rigorous and thorough review process, a systematic and clearly defined methodological framework was adopted, as illustrated in Fig. 1. Three essential stages make up this framework:

1) the searching phase, which involves setting clear search boundaries and carefully filtering results to ensure relevance;
2) the analysis phase, which includes utilizing bibliometric tools and conducting an in-depth investigation of studies that are directly related to the core topic of the review;
3) the discussion phase, during which the primary outcomes of the research are collected.

Each of these stages will be discussed in detail to provide a clear understanding of the procedural aspects involved.

2.1. Searching phase

The Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement published in 2020 [16] was adopted during the research to ensure the completeness and replicability of the study. The review discussed in this paper was performed by referring to two of the most well-known scientific databases, Web of Science [17] and ScienceDirect [18]. The cited databases were cross-referenced to ensure comprehensive coverage of scientific contributions in English. As no single available scientific database includes all the studies produced [19], the concurrent and combined research from two different sources was meant to complement the results obtained. The advanced research tools offered by the databases were used to orient the research using queries with Boolean

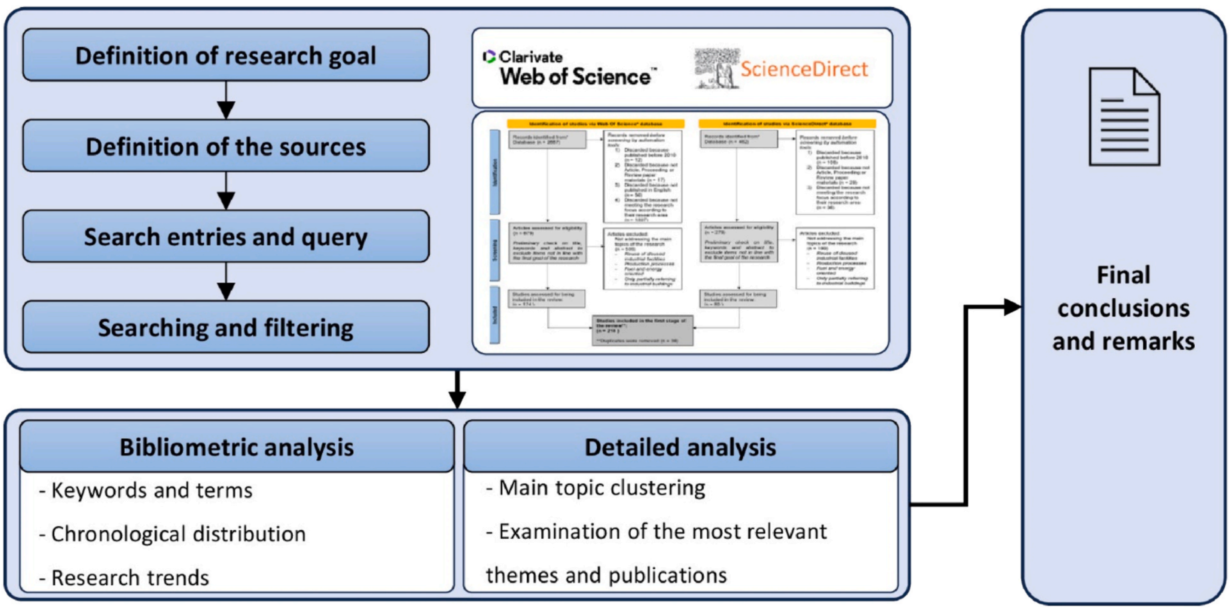

Fig. 1. Schematic overview of the research method.

operators for inclusion or exclusion criteria. The key terms and the research strategy adopted are presented in Fig. 2. Two main categories of keywords were used: one referring to the specific building type of interest and the other relating to the different possible topics covered by the publications. For the latter, the research was refined to encompass the different types of building installations or the structural issues investigated. Due to the limitations of the ScienceDirect search tool, multiple search queries were needed to investigate one topic at a time. In Fig. 3 the main steps of the searching phase are reported.

Other filtering criteria were imposed limiting the review to scientific articles, proceedings or review papers published in English after 2010. At the same time, studies not meeting the research area of interest according to the classification proposed by the online catalogues interrogated, were discarded. A two-stages checking procedure of the papers assessed for eligibility was then applied considering at first the titles, the keywords and the abstracts and later performing a general overview of the content of each paper. Studies only partially dealing with industrial facilities were discarded. In particular, the publications excluded were dealing manufacturing processes, production energy needs, and the reuse of disused old factories buildings. At the end of the screening procedure, 142 studies were collected from Web of Science database and 101 from ScienceDirect. The two sets were merged and duplicates excluded to achieve a final set of 203 studies to be included in the review.

2.2. Analysis phase

Following the selection of the studies, a bibliometric analysis was performed utilizing the VOSviewer software [20], open access, freely available online (VOSviewer Visualizing Scientficic Landscapes)(VOSviewer Visualizing Scientficic Landscapes) and recognised as one of the most promising computer-aided review tools one in science mapping application [21,22]. Its successful implementation in various literature applications have been documented [23] and it proved to be especially suitable for the analysis of emerging research fields in recent years [24]. In the study here presented, VOSviewer was implemented to perform a general and preliminary overview of the corpus of publications selected. The co-occurrence of keywords and terms was investigated in this stage and graphically mapped. To maintain simplicity and efficiency, full counting analysis algorithms were preferred over fractional counting ones, given the limited number of publications and streamlined procedures required [25].Following the evidence of the bibliometric analyses, the author meticulously examined the scientific contributions, categorizing them into distinct thematic clusters and subclasses.

3. Results and discussion

The bibliometric analysis involved a total of 203 papers, obtained after the identification, screening and selection process described in the previous section. At first, the chronologic distribution of publications over the years was considered highlighting a general increase in interest in the topic, as proved by the trend illustrated in Fig. 4.

A keywords co-occurrence analysis using VOSviewer was later conducted, focusing on keywords with a minimum occurrence value equal to 3The number of repetitions of keywords associated with each publication was evaluated to assess their mutual relative connections and highlight the main research areas. The analysis revealed 23 items, grouped into 6 clusters as shown in Fig. 5 and detailed in Table 1.

The 6 clusters mainly refer to structural and seismic issues (Cluster 1), building performance and energy (Cluster 2,3 and 4) and environmental-related topics (Cluster 5). Cluster 1 and 4 have no direct connections with the others, suggesting the lack of studies considering at the same time structural deficiencies, energy policies and building performance issues. Cluster 6, containing a single word, can be considered as an outlier value due to the more general topic addressed. With the same approach, a similar analysis was performed to create a co-occurrence map of the most used terms. In this case, 73 items were retrieved, grouped by the software in 9 clusters as shown in Fig. 6 and detailed in Table 2. The results of this second mapping process are widely overlapping with the previous one. Considering the terms used in literature instead of keywords allowed to deepen the analysis to point out specific topics within the research areas previously assessed. Anyway, some unclear or puzzling clustering criteria seemed to be applied in this case leading to an excessive fragmentation of clusters or the inclusion of terms not properly matching the discipline of the others. For this reason, a further check by the author on the effectiveness of the clustering procedure was needed, as expressed also by other studies in the literature that recommend using computer-aided bibliometric tools for preliminary results to be later refined with more accurate

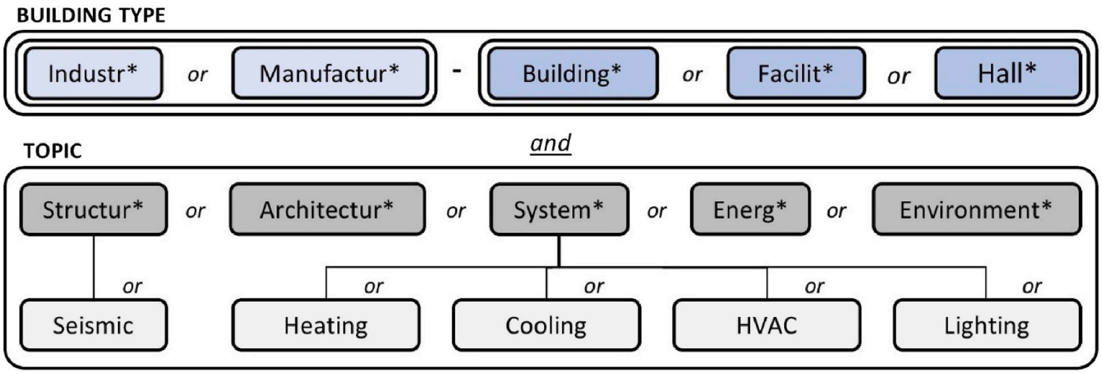

Fig. 2. Definition of the search queries adopted in the research.

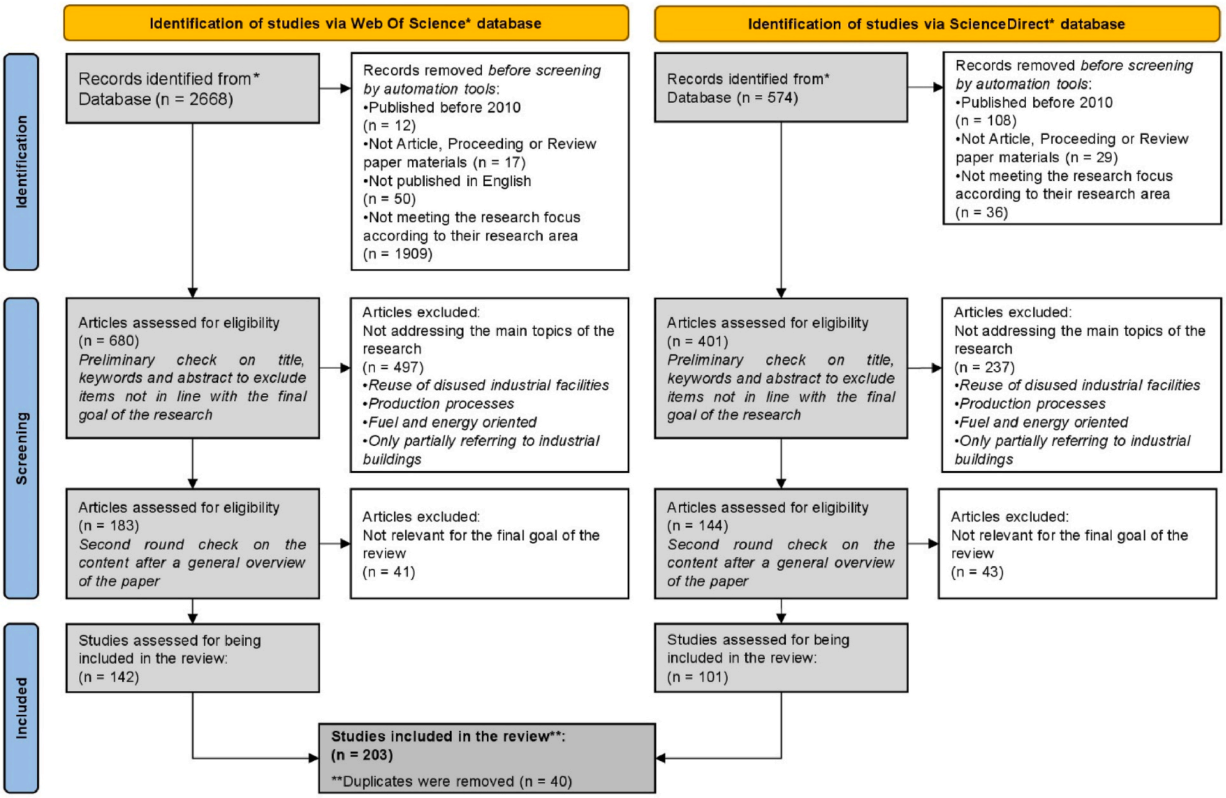

Fig. 3. PRISMA 2020 flow diagram illustrating the identification, screening and inclusion of the publications retrieved in literature.

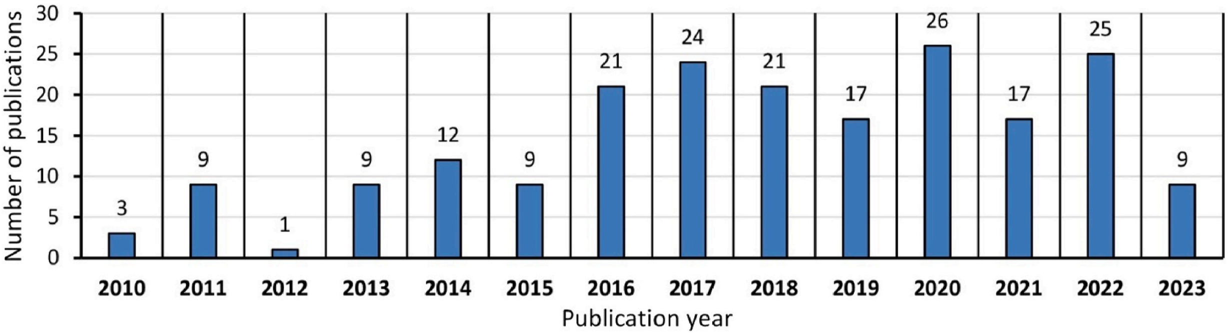

Fig. 4. Distribution of publications over time.

approaches [26].

Following the evidence obtained through the bibliometric analysis, 3 different overarching research topics were identified to propose a classification of the 203 publications included in the review and to overcome the excessive fragmentation of the VOSviewer mappings. Considering the results of keywords-based clustering, the publications in Cluster 1 discuss structural related topics and were hence pointed out as a sufficiently homogeneous set: the category "Structural issues and seismic performance" was directly derived, with a total of 88 publications that represent about 43 % of the total. On the other hand, studies in Clusters 2, 3 and 4 required a deeper analysis since their remarkable variety of approaches and targets even if they all address building performance and efficiency. However a distinction was made between publications more focused on energy related features and the ones dealing with building scale analyses in terms of envelope components or systems. The latter were merged with studies included in Cluster 5, that focus on the same themes but with an LCA-oriented approach. Following these considerations, the categories "Energy" and "Building performance" were proposed, including 45 and 70 studies respectively.

The result of the categorization procedure over exposed is reported in Fig. 7 along with the number of studies associated with each theme and the percentage concerning the total amount of studies.

In Fig. 7, a graph showing the research trends over years is also presented. Structural and seismic response of industrial facilities

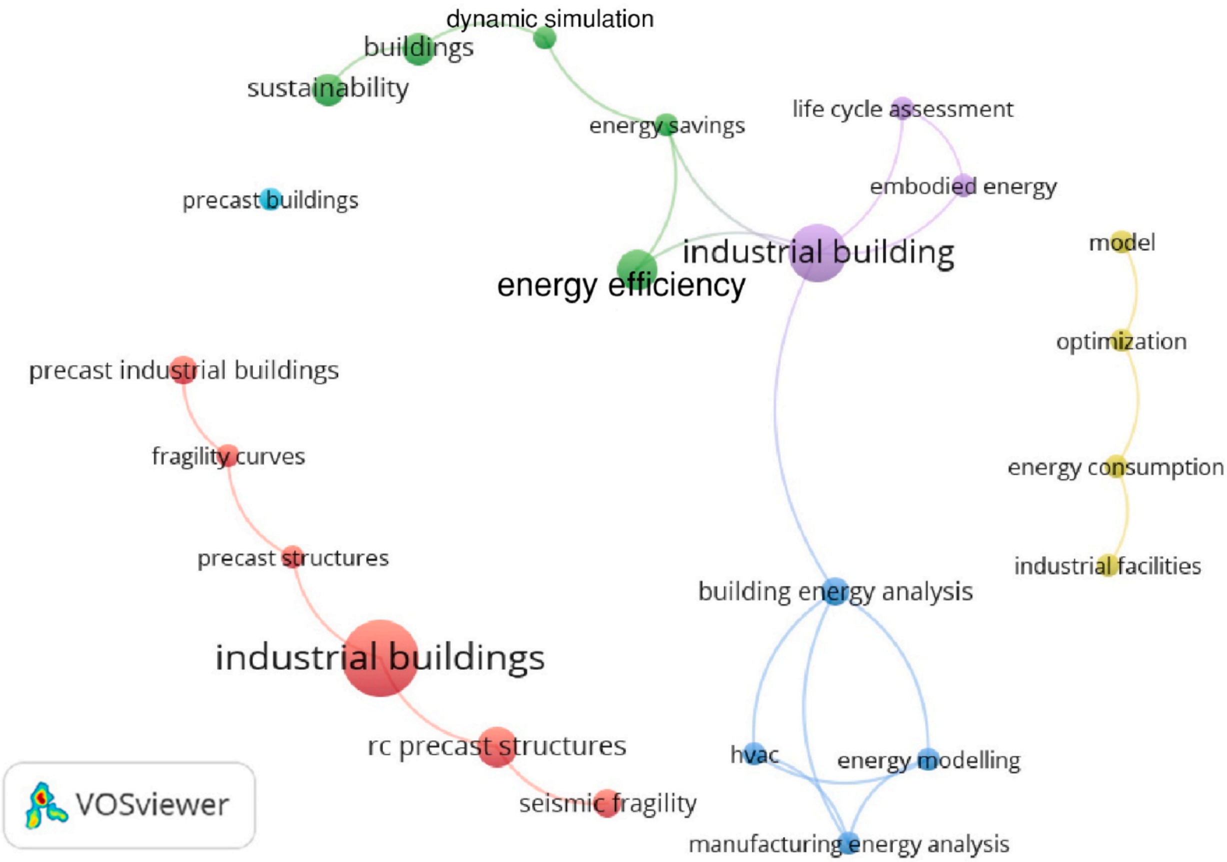

Fig. 5. VOSviewer visual map of keywords co-occurrence. The size of the spheres expresses their incidence in the literature while the mutual distance is representative of the correlations between them.

started to be frequently addressed as a reference topic up to now starting from 2014, partially due to the consequences of seismic events occurred in the previous years that made the theme particularly relevant. On the contrary, energy and building performance connected to industrial facilities can be considered emerging fields. The former is still not widely discussed as certified by the generally limited amount of publications even if a growing trend can be detected in recent years, while the latter present a quiet inconstant trend over the most recent years but with significative spikes in 2016 and 2022 that presents the highest number of published researches. Within each category, further subclasses were later identified considering each publication's specific theme as it will be covered in the following sections. The significance of each class and subclass was then evaluated to determine their relevance in the scientific research landscape. Lastly, a systematic investigation was conducted on the scientific contributions that met the current review's objective, highlighting their unique features, the utilized tools and pertinent findings. To provide a more effective presentation of the results obtained, each theme will be discussed in the following sections following the classification proposed by the author.

3.1. Building performance

Given the final goal of the review here proposed, the contributions referrable to the building performances will be presented in detail to illustrate the main research approaches adopted and some highlights of the findings available in the literature. Several subtopics were retraced for this field and consequently analysed to present the different aspects connected with the theme as listed in Fig. 8. The majority of the studies available is focused on HVAC and indoor conditions in industrial facilities. Retrofit solutions are still not widely explored for this kind of buildings as well as the theme of sustainability associated with production facilities. Indoor lighting conditions are specifically addressed by 7 publications retrieved in the literature. To conclude, some studies about the application of BIM methodologies were also included in this section since their contribution to the comprehensive evaluation of the performance of existing industrial facilities is evaluated.

3.1.1. Sustainability

The 13 publications about sustainability issues retrieved, can be grouped into two main categories. The first one includes studies about rating systems and sustainability indexes to be adopted in the case of industrial facilities [27–30]. The remaining articles in the literature deal with life cycle analyses, regarding both the environmental and economic sustainability of industrial buildings. The environmental and energy impact is analysed by considering single facilities [31] and specific construction techniques, as in the case of

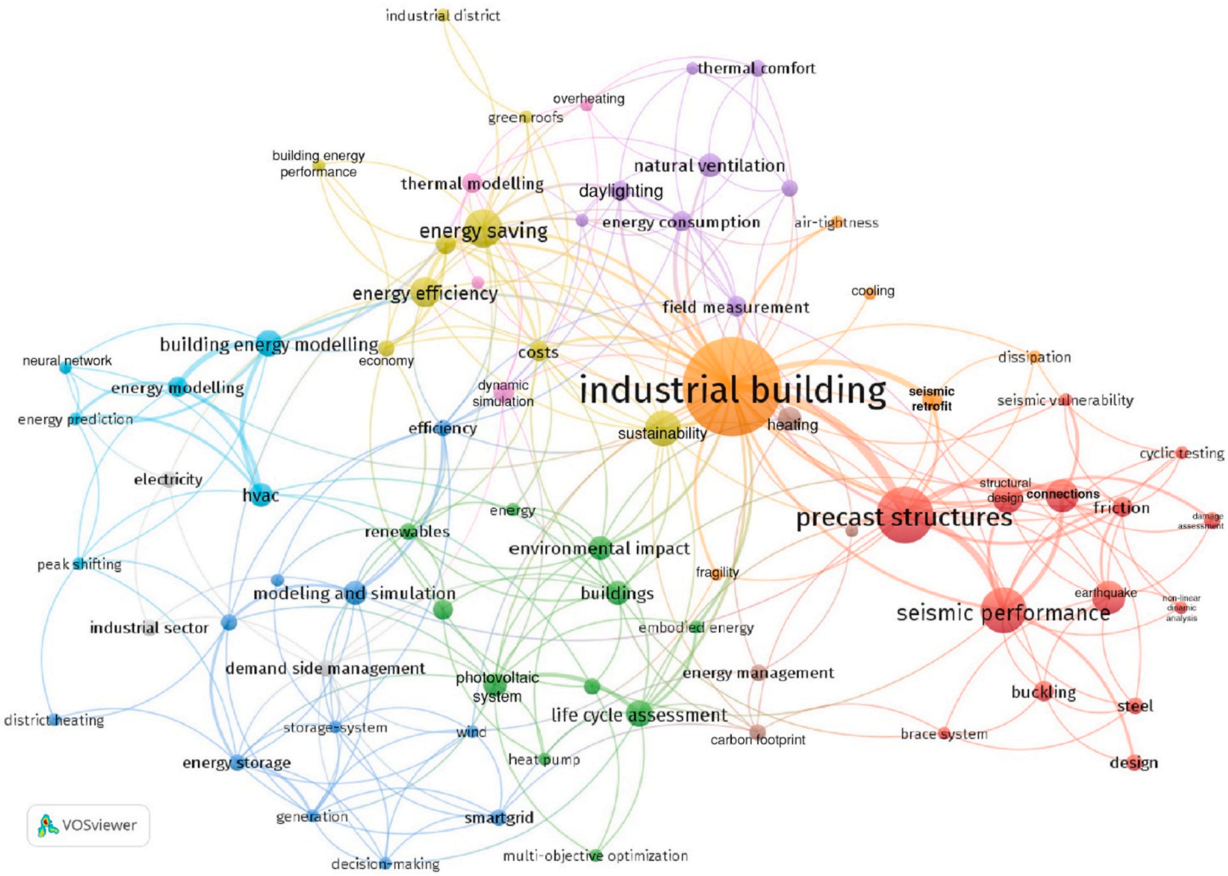

Fig. 6. VOSviewer visual map of terms co-occurrence.

Table 1
Keywords clusters according to the bibliometric analysis produced by VOSviewer.

Cluster	Colour	Number of terms	Terms
1	Red	6	Fragility curves Industrial buildings Precast industrial buildings Precast structure Seismic fragility
2	Green	5	Buildings Dynamic simulation Energy efficiency Energy saving Sustainability
3	Blue	4	Building energy analysis Energy modelling HVAC Manufacturing energy analysis
4	Light green	4	Energy consumption Industrial facilities Model Optimization
5	Purple	3	Embodied energy Life cycle assessment Industrial building
6	Light blue	1	Precast buildings

studies specifically dealing with precast concrete buildings [32,33]. Life Cycle Assessment (LCA) techniques were applied also to evaluate different strategies to ensure high sustainability standards in the case of a newly built facility [34]. Moreover, studies focusing on single-building components such as structural frames [35], roofing panels [36] and facades [37] are available. The construction and

Table 2
Terms clustering proposed by VOSviewer.

Cluster	Colour	Number of terms	Terms
1	Red	14	- Brace system -Buckling -Connections -Cyclic testing -Damage assessment -Design -Earthquake -Friction -Nonlinear dynamic analysis -Precast structures -Seismic performance -Seismic vulnerability -Steel -Structural design
2	Green	11	-Buildings -Embodied energy -Environmental impact -Heat pump -Life cycle assessment -Multi-objective optimization -Parametric study -Photovoltaic system -Renewables -Solar energy
3	Blue	11	-Decision-making -Demand-side management -District heating -Efficiency -Energy storage -Generation -Modelling and simulation -Optimization -Smart grid -Storage-system -Wind
4	Light green	9	-Building energy performance -Costs -Economy -Energy efficiency -Energy saving -Green roofs -Industrial districts -Life cycle cost -Sustainability
5	Purple	8	-CFD simulation -Daylighting -Energy consumption -Field measurement -Large space building -Natural ventilation -Skylights -Thermal comfort
6	Light blue	6	-Building energy modelling -Energy modelling -Energy prediction -HVAC -Neural networks -Peak shifting
7	Orange	6	-Air-tightness -Dissipation -Evaporative cooling -Fragility -Industrial building -Seismic retrofit
8	Brown	4	-Analytic hierarchy process -Carbon footprint -Energy management -Heating

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Table 2 (*continued*)

Cluster	Colour	Number of terms	Terms
9	Pink	4	-BIM -Dynamic simulation -Overheating -Thermal modeling

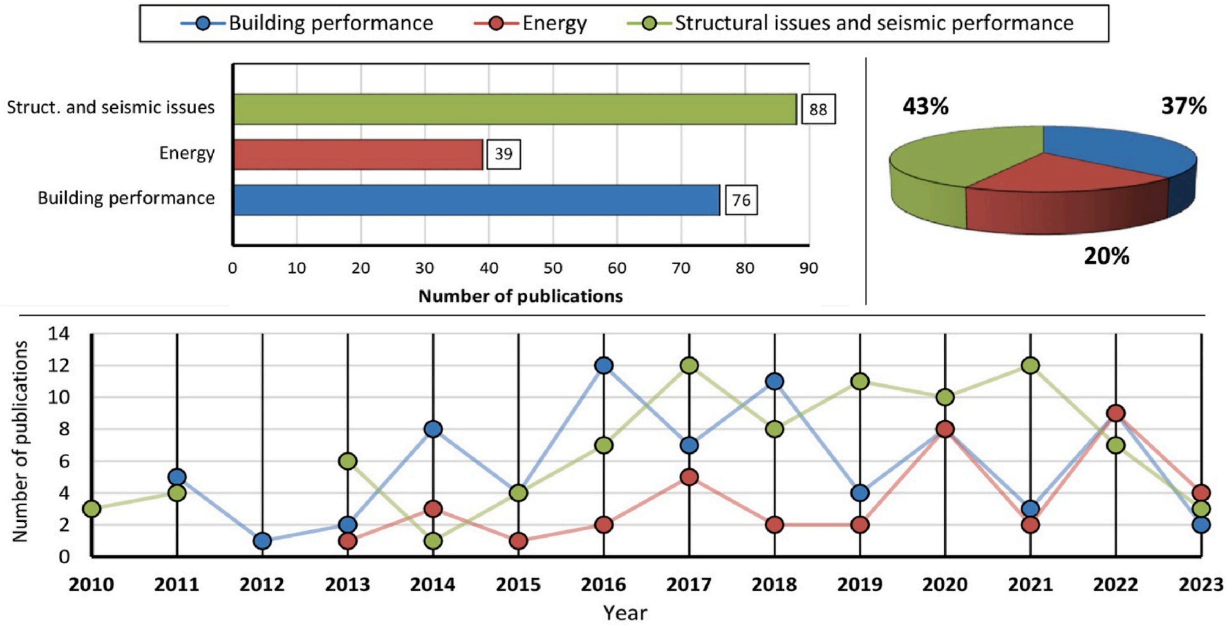

Fig. 7. Research trends over the years according to the classification proposed by the author.

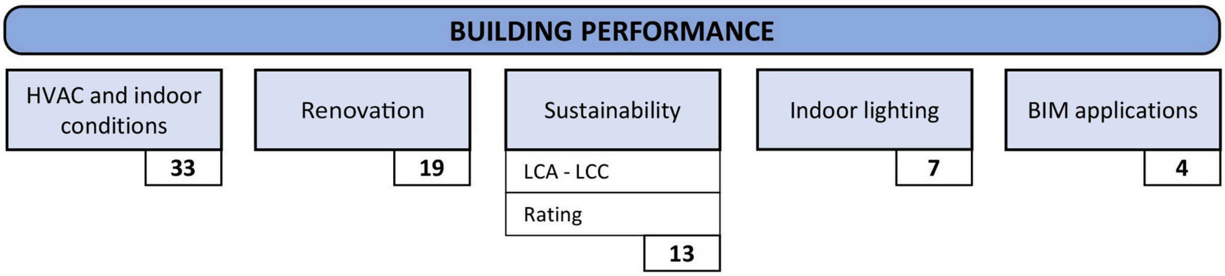

Fig. 8. Building performance related publications: subtopics and number of studies.

operational costs are furthermore used to compare traditionally designed industrial buildings and sustainable ones [38]. However, only one research was retrieved performing at the same time LCC and LCA analyses at building scale [39], implementing in this case a BIM-based optimization procedure for decision making in the design stage.

3.1.2. Renovation

Eighteen publications, outlined in Table 3, focus on renovation interventions to be applied to existing industrial buildings, considering individual facilities and wider building stocks. The latter were investigated in 3 research works, considering Irish and Italian scenarios. Horan et al. performed a national scale assessment to estimate the decarbonisation potential of PV installation and water harvesting technologies on the roofs of buildings in commercial and industrial districts in Ireland [40]. The wide roof surface of this kind of facilities was proved to be an enhancing factor for the effectiveness of the measures evaluated. In Mediterranean area, industrial districts can be exposed to potential discomfort conditions, primarily connected with summer heat waves, as evidenced by Guerri et al. in the metropolitan area of Florence (Italy) [41]. Acting on the urban layout or on the share of vegetated and built areas, the authors pointed out a potential reduction of Land Surface Temperature up to 2 °C. A similar approach is proposed by Ciacci et al. which also estimate the effects on environmental parameters and pollutant concentrations at urban scale through the implementation

Table 3
List of publications about renovation strategies in the literature. In each row, a general overview of each study is provided by indicating the publication year, the location of the case study building along with the climate characteristics according to Koppen classification when available, the measures evaluated, the focus of the analysis, the software used, and the key results.

Ref.	Year	Location	Energy saving measures	Focus of the analysis	Software	Main results
[48]	2013	Kosice (SK) Dfb-	Automated integration in: -Lighting; -Heat recovery; -Door operation.	-Energy performance; -Thermal comfort.	ESP-r BuildOpt-VIE	Energy saving potential of about 10–60 %
[45]	2014	Oss (NL) Cfb	Tetrafluoroethylene monomer fluorocarbon coating	-Energy performance; -Surface temperature; -Thermal comfort.	DesignBuilder EnergyPlus	-Roof's albedo increased by 120 % (from 0.3 to 0.67); -73 % decrease in cooling demand; -5 % increase in heating demand.
[51]	2014	Amsterdam (NL) Cfb	-Building thermal insulation; -Airtightness improvement; -Skylights.	- Energy performance;	TRNSYS DAYSIM MODEFRONTIER	-Lighting consumption prevails over heating and cooling demand; -The optimized solution is highly dependent on the internal thermal loads.
[53]	2014	Bologna (IT) Cfa	-Building thermal insulation; -Windows substitution; -Gas-boilers substitution; -Heat recovery; -Variation of the heating set point.	-Energy performance; -Cost analysis.	MC4 Suite	Combination of retrofit measures can produce: -15 % decrease in energy demand; -100000 € economic saving; Less than 6 years pay-back time.
[49]	2016	Beijing (CN)		-Energy performance assessment	No information	-Assessment of poor performance factors: air leakages (3.1 ACH), condensation, poor insulation, low standard HVAC and air distribution.
[52]	2016	Helsinki (FI) Dfb	-Walls insulation; -Roof insulation; -Windows substitution; -Doors substitution; -Ventilation system and heat recovery; -LED lighting.	-Energy performance; -Cost analysis.	IDA-ICE v4.7	-Envelope retrofit may not beneficial within a payback period of 20 years; -Heat recovery adoption is the most cost effective solution; -LED lighting is highly beneficial; -A combination of the different measures is the most recommendable solution.
[58]	2016	Ulsan (KR) Cfa	-PV installation; -Roof insulation; -Skylights installation, -Lighting dimming control.	-Energy performance; -Cost analysis.	EnergyPlus MATLAB	-Energy optimal solution results in LCC reduction equal to 11,5 %: o PV panel ratio: 65 %; oSkylight ratio: 17,8 %; oInsulation thick: 0,26 m; -Cost optimal solution results in LCC reduction equal to 27,3 %: oPV panel ratio: 1 %; oSkylight ratio: 17,8 %; oInsulation thick: 0,26 m.
[56]	2016	Berndorf (AT) Cfb	Scenario 1: -Windows substitution; -Roof insulation; Scenario 2: -Windows substitution; -Roof substitution; -Skylights substitution.	-Energy performance; -Thermal comfort.	Revit OpenStudio x SketchUp EnergyPlus	-Heating demand reduction up to 52 % -Overheating reduction: oS1: - Avg. T reduction: 0.2 °C -Max. T reduction: 2.3 °C oS2: -Avg. T reduction: 2.1 °C -Max. T reduction: 6.3 °C
[55]	2017	Berndorf (AT) Cfb	-Night natural ventilation; -Cool roof elastomeric coating; -External shading on south façade; -Roof insulation; -Skylights substitution; -Windows substitution.	-Energy performance; -Thermal comfort	Revit OpenStudio x SketchUp EnergyPlus	-Effective prevention of summer overheating; -Cool roof and solar shading give significant results in case of low internal loads.
[47]	2017	South California (USA)	-AHUs; -Chillers refrigerators; -High efficiency fluorescent lamps.	-Energy performance; -Cost analysis.	No information	-The highest annual energy and cost savings is ensured by AHU, followed by lighting, and then the chillers
[46]	2018	Malaysia	-Active and passive cool roof system with ventilation in air cavity and reflective coating	-Energy performance; -Surface temperature; -Thermal comfort.	Experimental study	-Reflective coating reduce the metal roof surface temperature by 7 °C; -Integration of reflecting coating and air cavity ventilation reduce the attic temperature by about 13 °C.

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Table 3 (*continued*)

Ref.	Year	Location	Energy saving measures	Focus of the analysis	Software	Main results
[43]	2018	Trieste (IT) Cfa	-Cool roof installation; -Green roof installation	-Energy performance; -Cost analysis; -Social impact.	No information	-From the private investor's viewpoint cool roof is more advantageous; -Economic incentives are needed to promote the spread of green roofing; -Cost-benefit analysis favourable for the green roof because of its positive externalities and social impact.
[50]	2019	China	-Passive energy savings measures; -Efficient utilization of HVAC and lighting systems; -Renewables and heat recovery.	-Energy performance.	eQUEST	-Average reduction of about 16 % in energy demand; -Heating and humidification systems show the greatest energy saving potentials; -Climate conditions influence the results.
[40]	2020	Ireland (IE)	-PV installation; -Water harvesting solutions.	-Rooftop decarbonisation potential.	QGIS	-Prioritizing decarbonisation actions for the larger buildings; -PV installation results in up to 513 ktCO2 savings; -PV installation results in GHG reduction equal to 4 %; -Rainwater harvesting technologies result in 6 ktCO_{2e} savings.
[54]	2020	Valenzano (IT) Csa	Combination of: -Windows substitution; -External automatic shading installation; -Heat recovery; -PV installation; -Optimization of HVAC flow rates; -Variation of heating set point.	-Energy performance; -Cost analysis.	DesignBuilder EnergyPlus MATLAB	-Energy savings up to 81 %; -Economy savings up to 45 %; -Prioritization of measures: 1) PV system; 2) Heat recovery; 3) HVAC schedule optimization.
[57]	2020	Durres (AL) Csa	Scenario 1: -Walls insulation; -Roof insulation (S1/S2); Scenario 2: -S1; -Skylights substitution; -Increased summer ventilation.	-Energy performance; -Thermal comfort.	DesignBuilder EnergyPlus	-8 % (S1) and 14 % (S2) decrease in cooling energy demand; -13 % (S1) and 19 % (S2) decrease in heating energy demand; -1 °C (S1) and 1,5 °C (S2) decrease in internal temperature during summer.
[44]	2020	Mexico BSh, BSk, BWh, BWk, Cwa,Cwb	-Cool roof; -Roof insulation; -Walls insulation; -PV installation.	-Energy performance; -Cost analysis.	SketchUp TRNSYS	-Warm cities require the implementation of a cool roof on a non-insulated roof or its insulation; -Roof insulation is effective in temperate climates; -Walls insulation reduce the payback period in case of heating system installation;
[59]	2021	Liverpool (UK) Cfb	-Walls insulation; -Floor insulation; -PV installation.	-Energy performance; -CO_2 emissions.	IESVE	-Energy demand and CO_2 emissions reduction by 56 % acting on building envelope; -CO_2 emissions reduction by 56 % installing PV.
[41]	2022	Florence (IT) Cfa	Changes in: -Building area; -Surface albedo; -Trees coverage percentage; -Grassland area.	-External temperature; -Land surface temperature.	Landsat data QGIS	-50 % of industrial buildings located in hot-spot areas; -Increasing vegetated areas and reducing built one result in a 2 °C drop in LST.
[42]	2023	Barberino di M. llo Csa	-Green roofs; -Trees planting	-Energy performance; -Environmental parameters; -Pollutant concentration.	ENVI-met DesignBuilder	-External air temperature reduced by 1.5 °C; -Outer surface temperature reduced by up to 15 °C; -Wind speed at roof level reduced by 50 %; -Effective particulate absorption effects; -15 % energy savings for both cooling and heating demand;

of green roof solutions in case of an industrial area in Tuscany [42]. Green roofing is proposed as a retrofit measure also by Berto et al. for an industrial building in Northern Italy, remarking its positive social implications but highlighting at the same time uncertainties about the economic profitability of similar interventions [43]. Most of the publications deals with retrofit initiatives at building scale with applications to real case studies. These industrial facilities are different in terms of country, climate conditions, construction technology, hosted activities, and retrofit measures proposed. Some of the publications focus on the improvement of building envelope component performance exclusively. Espino-Reyes et al. recommend retrofit measures addressing roofing components considering PV installation, coupled with insulated or cool roof in hot and temperate climate zones in Mexico [44]. The adoption of a cool roof solution is proposed also by Mastrapostoli by implanting a tetrafluoroethylene monomer fluorocarbon coating that results in a remarkable reduction in cooling energy demand during summer [45]. The effect of reflective coating on the roof can be furthermore enhanced when coupled with an air cavity layer and its ventilation [46]. Studies considering only building installations are also available, as the one by Kim that compares interventions on air handling units, refrigerators and lighting system within a life cycle cost perspective [47]. Katunsky et al. highlight the effectiveness of the application of automation and control in lighting and heat recovery system and apertures operations [48]. Anyway, retrofit oriented studies usually evaluate multidisciplinary redevelopment measures due to the overall low performances of these buildings [49], considering also the specific needs of production activities and climate characteristics as in the research by Wang et al. [50]. For instance, excessive insulation levels should be avoided in case of process loads with high indoor heat generation [51].Authors can refer to economy related parameters when prioritizing redevelopment strategies. In this case, as stressed by Simson et al. [52], measures addressing only the building envelope performance might not be economically advantageous in a mid/long-term payback period. For this reason, a combination of different interventions should be preferred, as proved by the evidence derived by Dongellini et al. [53]. Also Ascione et al. [54] remark the economical profitability of acting on system and building installations instead of refurbishing envelope components. The same study assesses energy saving up to 81 %, achievable including PV installation that it proves to be the most valuable intervention. In the literature, contributions considering only energy performance and internal comfort are also available. Gourlis et al. deeply investigate an existing historical industrial facility in Austria to prevent summer overheating conditions [55]. Increasing the roof's albedo, enhancing its thermal insulation, and reshaping the existing skylights prove to be effective when coupled with a rescheduled night natural ventilation. At the same time, cool roof coating and solar shaders installed on external walls are recommendable only in case of low internal loads. The same authors also apply different retrofit scenarios to ameliorate the energy performance of the same building [56]. Heating energy saving up to 52 % can be achieved in this case along with a significant decrease in summer overheating, particularly sensible in case of the integral substitution of both roof and skylights components. A similar approach was also adopted by Dervishi et al. [57] but with less effective results in terms of energy savings and overheating prevention, due to the different climate conditions, age and construction technology of the building considered. To conclude, some general considerations can be made with respect to the methodological approach followed in the studies selected. In order to ensure reliable results, most of the contributions are based on on-field measurement and real-time monitoring of indoor environmental parameters. As for the calculation engines implemented in energy modelling and simulations, EnergyPlus is the most adopted in this field also because of its interoperability with external software such as Matlab and its integration

Table 4
List of papers about indoor lighting conditions. In each row, a general overview of each study is provided by indicating the publication year, the location of the case study building when available, the measures evaluated, the focus of the analyisis, the software used, and the main results.

Ref.	Year	Location	Energy saving measures	Type of analysis	Software	Main results
[65]	2013	London (UK)	Optimized combination of: -On/off lighting control; -Natural ventilation.	-Energy performance; -Thermal comfort; -Lighting conditions.	EDSL TAS Lumen Designer	-70 % decrease in lighting energy demand; -Reduction of overheating hours thanks to lighting control and natural ventilation; -45 % decrease in CO_2 emissions.
[66]	2014	Tianjin (CN)	-Continuous/off lighting control; -On/off lighting control; -Vertical and horizontal skylights.	-Energy performance; -Lighting conditions.	Radiance Autodesk Ecotect EnergyPlus	-36 % and 42 % decrease in lighting energy demand; -7 % and 9 % increase in heating energy demand.
[64]	2015	Xi'an (CN)	-Skylights; -Optimized distribution of lighting devices; -Lighting control sensors network.	-Energy performance; -Lighting conditions.	DIALux Autodesk Ecotect	-Up to 80 % decrease in lighting energy demand during cloudy days;
[67]	2017	Kosice (SK)		-Lighting conditions	Radiance	-Natural lighting alone is not sufficient; -Skylights ensure about 30 % of the observed daylight factor values.
[63]	2019	Coimbatore (IN)	-Continuous/off lighting control; -On/off lighting control; -Skylights.	-Energy performance; -Lighting conditions.	Velux Daylight Visualizer Velux EIC Visualizer	-25 % and 31 % decrease in lighting energy demand
[62]	2019	Athens (GR)	-Saddle roof openings; -Horizontal roof skylights; -Vertical roof openings.	-Lighting conditions	DIVA for Rhinoceros	-Sawtooth configuration with an average distance of 10–13 m is the best performing one
[61]	2022	Kosice (SK)	-Saddle roof openings; -Horizontal roof skylight; -Vertical roof openings; -Lanterns skylights.	-Lighting conditions	Radiance	-Roof-lighting is more efficient than side-walls windows for lighting purpose; -Saddle roof openings with diffuse glazing are the best performing one.

with BIM environment with dedicated plugins.

3.1.3. Indoor lighting

Visual comfort and the lighting related consumptions are appointed as crucial factors in the literature when evaluating industrial buildings performance. The main influential publications retrieved in the literature about this topic are listed in Table 4. As observed by Katunsky et al. analysing a existing manufacturing hall in Slovakia, natural lighting alone is not sufficient to meet the standard level required [60]. The same authors highlight the significant contribution of skylights, capable of ensuring about 30 % of the observed daylight factor values. The effectiveness of roof-lighting over side-walls windows is assessed also by Dolnikova et al. that propose a comparison of different skylights configurations [61]. According to their findings and to the ones by Mavridou et al. after applying a parametric optimization [62], saddle roof openings are the best performing solution. Several studies explore the effects of a combined implementation of roof skylights and lighting control systems. Different energy savings percentages are reported in the literature connected to these solutions, ranging from about 30 % [63] up to 80 % when the adoption of a sensors network and the optimized distribution of lighting devices is considered [64]. Further considerations can be formulated by analysing also other thermal aspects connected with internal lighting. Wang et al. claim that exploiting lighting control and natural ventilation, overheating hours can be sensibly diminished as well as lighting energy demand and CO_2 emissions [65]. However, when considering winter months, the reduction of thermal internal loads connected with the limited operation hours of lighting devices, a slight increase of heating energy needs about 7 %–9 % can occur [66]. For this field of research, several software are available for lighting simulations; however, referring to the publications analysed, Radiance seems to be the mostly used even.

3.1.4. HVAC and internal conditions

Most of the publications about industrial building performance deal with indoor environment conditions and HVAC systems but the variability of production activities and climate conditions is a great source of uncertainties when trying to formulate general considerations. The influence of building's location on annual energy consumption ranges from −10 % to +8 % according to Diaz-Elsayed et al. [68] and its incidence is remarked also in other studies in the literature [69]. Despite these limitations, Labat et al. [70] estimated a comparable impact of process, HVAC and lighting demand on the final energy balance of different case studies buildings in France. At the same time, different working operations result in different occupancy schedules, activity levels and different internal loads connected to the machinery required. Bawaneh et al., after an extensive review of data about several USA facilities, pointed out an average non-process related energy consumption of about 28 W/m^2 when heating, cooling and lighting systems are installed [71].

Given the peculiarities of industrial buildings and the relevance of internal thermal loads, Mawson et al. recommend the adoption of proactive HVAC systems capable of interact with process related demand [72]. Depending on the type of the activities performed, the presence of contaminants and the related indoor air quality concerns should be also carefully examined through evaluation indexes specifically dedicated for industrial environments [73] as well as adopting multicriteria approach when designing a proper ventilation system [74]. As for workers wellbeing, innovative techniques coupling the results of real-time indoor monitoring and the outputs of subjective surveys among the employees are presented in the literature [75]. Another theme is related to external door opening operations, influencing both airflows and indoor temperature [76] as well as external infiltration. As stressed by Brinks, such a contribution to the thermal and energy balance is usually accounted using conventional formulations included in national regulations, leading to unclear and often incorrect estimation [77]. The minimization of air-leakages is highly recommended in an energy saving perspective as stressed by Tanasic et al., whose study highlights possibly misleading outputs of energy simulations when compared to real experienced data in terms of internal air temperature [78]. The latter is particularly exposed to stratification phenomena because of the considerable internal height of the industrial halls. During warmer months, a vertical temperature difference profile of about 0.3 °C/m - 0.7 °C/m is registered by Porras et al. [79]. The influence of outdoor temperature on the stratification of indoor air is significant, with some mitigation observed when air conditioning systems are installed, as demonstrated in various studies. Kurnitski et al. report lower values in colder climates, indicating a limited efficacy of air heating systems in properly control internal conditions [80]. Ahmed et al. corroborate these findings also advocating for the preference of ceiling mounted radiant panels, over air heating units in case of low air change rates [81]. Radiant floor heating can be a cost and energy saving solution thanks to its thermal storage potential, allowing to run heat pumps generators at night when electricity price is generally lower [82]. For all-air solutions, building envelope integrated solar collectors can pre-heat external air and reduce the energy demand [83–86]. Internal air distribution methods are studied in the literature considering natural [87], mechanical [88] and hybrid ventilation [89] highlighting some critical operative conditions and energy over usages. Appreciable cost and energy savings can be furthermore achieved by simply acting on setpoint operating schedule [90,91] and reducing external air supply rates [92]. Cooling strategies are also investigated, emphasizing the possible the possible exploitation of natural free cooling [93] as expressed by Nezamdoost et al. and HVAC solutions. De Angelis et al. underline the role of thermal internal gains on internal environment conditions and advocate for mechanical ventilation systems, highlighting the energy-saving potential of indirect evaporative cooling in humid climates [94]. Guan et al. evaluate the performances of a control air-conditioning system based on liquid desiccant, capable of ensuring about 23 % energy savings furtherly improvable by optimising airflow ratios [95] while evaporative cooling is also tested by Kowalski et al. referring to Poland regions [96]. According to their study, indirect evaporative solutions using external air should be preferred over the ones using exhaust air recirculation. To conclude, Wang et al. evaluate variable speed driven chilled and cooling water systems for a high-tech industrial facility in Taiwan assessing energy savings between 5 and 30 % based on different water temperatures and weather conditions [97]. When performing an overall assessment of industrial buildings operating conditions, both energy demand and comfort should be encompassed as performed by Zhou et al. considering all the influencing parameters [91]. A multi-parameter and comprehensive approach is also adopted by both Chinese et al. and Bac et al. to produce a critical selection of heating-oriented HVAC solutions for medium-sized manufacturing facilities, applying a a wide set of evaluation criteria [98,99].

3.1.5. BIM applications

A recent trend in the literature is related to the application of Building Information Modelling (BIM) methodologies to manufacturing facilities. Table 5 collects the main features of these studies. Garwood et al. illustrate the application of BIM to produce reliable Building Energy Models starting from a point cloud survey [100]. Gourlis et al. emphasize the advantages achievable through similar approaches for the simultaneous evaluation of systems, machines and processes resulting in energy savings and foreseeing future synergies and further developments towards the full exploitation of BIM potential [101]. The same authors recently deepen the research to validate a methodology for the definition of digital twins in manufacturing oriented facilities [102]. Moreover, as-built BIM models can be used as repositories to integrate data on building performances, as suggested in a publication about the assessment of water infiltrations on an existing facility's roof [103].

3.2. Energy

Coming to energy-related publications, 39 research works were retrieved in the literature dealing with different aspects, including both building-scale and regional-scale studies. A general overview is provided in Fig. 9, where the different subtopics are highlighted.

Energy generation and management are crucial to ensure a proper operational phase of industrial and manufacturing facilities and for this reason the theme is considerably discussed in the literature. In recent years, control and monitoring procedures for smart energy management are analysed. Validation of monitoring systems is reported in the literature [104] along with an evaluation power metering and management information systems [105]. Recently, the application of artificial intelligence technology is also experimented in this field with promising results [106]. Machine learning techniques in control strategy let to assess a reduction up to 15 % in peak energy demand by decoupling HVAC and production related loads [107]. Focusing on generation systems, combined heating and power generation is addressed by some authors as a promising solution for industrial buildings considering their multipurpose related energy needs and it shows remarkable potential from both an economic and environmental point of view. Machalek et al. assess reductions of about 10 % and 23 % in the annual primary energy demand and CO_2 emissions respectively with a payback period of 8 years approximately [108]. The latter can be furtherly reduced depending on the control strategy deployed, as retrieved by Calise et al. that propose an innovative hybrid electric-thermal load tracking [109]. The integration with renewables is also evaluated in the literature, because it is nowadays mandatory to comply with the goal of a carbon-free economy. A cogenerated cooling, heating and power system including solar panels, thermal storage and heat pump is evaluated by Herrando et al. as the optimal solution for an industrial building in Spain [110], since it performs even better than simply PV-based solutions that reduce the environmental impact by only 30 %. PV installation is evaluated by Abuzaid et al. with a life cycle approach in case of an industrial facility in the UAE. Given the great producibility of the plant in relation to irradiation conditions, the investment costs can be recovered in a relatively short period of time even if the decarbonisation of the production phase of the panels should be encouraged [111]. The economic aspect has to be particularly addressed when considering renewable applications in developing countries or not densely industrialized areas such as south Russia [112], Philippines [113], Bangladesh [114], Pakistan [115] and Trinidad and Tobago [116]. In these cases, the need for government subsidies and financial benefit to make it viable is remarked. To promote renewables sources exploitation, different solutions are however available such as ground source heat pumps [117] and biomass fuelled systems, capable of reducing energy dependence from grid and properly manage waste [118]. Due to their non-deterministic behaviour, energy production from renewables must deal with the possible unproper matching of power demand. Hence, a growing interest towards energy storage solutions for industrial applications can be retraced in the literature. The adoption of energy storage technologies enables the industrial companies to properly apply energy management procedures [119] and benefits from shifting the demand to off-peak hours with a consequent cost reduction by about 12 % [120,121]. According to Elio et al., air compressed storage is the one with the highest return on investment [122]. However, to overcome their extremely high initial investment costs, a correct sizing of storage batteries is crucial and can be achieved via decision theory's application [123]. Authors in the literature also stress the urgency of a general revision of

Table 5
List of papers about BIM applications in industrial buildings related studies. In each row, a general overview of each study is provided by indicating the publication year, the location of the case study building and its characteristics, the software used, and the key results.

Ref.	Year	Location	Case study	Software	Main results
[100]	2017	Sheffield (UK)	Factory 2050 building	Leica Cyclone Revit IES VE	- Conversion from Point Clouds to BIM and BEM models; -Accurate energy models can be produced.
[101]	2017	Berndorf (AT)	Historical metal-band cutting and forming factory; New construction bakery and meat factory.	Revit OpenStudio x SketchUp EnergyPlus	-BIM to BEM approach in industrial construction is a completely novel aspect; -Cost-benefit balance is generally highly advantageous; -Coupled simulation including building, systems, machines and processes would consistent energy savings; -Further developments of open interfaces are necessary for the full exploitation of BIM potential.
[103]	2022	Kolin (CZ)	House of Culture building		-Roof leakages assessment; -Integration with BIM model.
[102]	2022	Austria	New construction bakery and meat factory	Revit Dynamo	-Validation of a methodology for the definition of digital twins of manufacturing oriented facilities; -BEM application of BIM models.

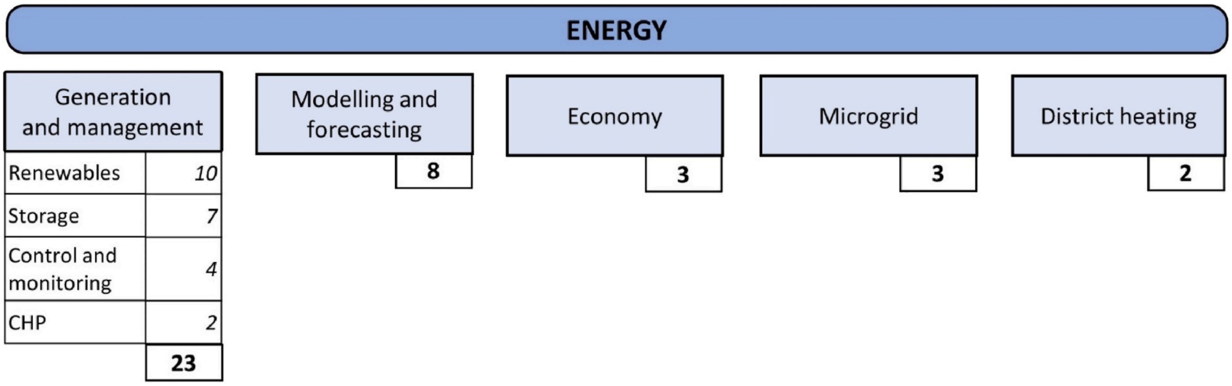

Fig. 9. Energy related publications: subtopics and number of studies.

electricity pricing rates and financial support to enable industrial energy storage deployment [124]. According to Camarero et al., even when compensations are foreseen for surplus energy, storage batteries may be not profitable unless a dramatic drop in their prices occur. Only when a self-consumption rate of 70 % is stated, PV systems including energy storage can be cost-effective [125]. A proper integration with energy production from renewables makes energy storage solutions economically interesting, as outlined by Arteconi et al. considering a thermal energy storage coupled with heat pump for cooling purposes [121]. Multigeneration solutions including photovoltaic, wind turbines and biomass or diesel burners [126] or tidal generation [127] to fuel industrial facilities are also considered in the literature.

Energy generation from renewables is evaluated in the recent years considering its integration within microgrids and shared energy consumption. Considering a mixed scenario of industrial and residential facilities Bartolucci et al. assess that load profile and PV plant are the most influencing factors to reduce dependency on grid and to properly manage the storage battery [128]. A real existing industrial microgrid is also tested in the literature and improvements suggested recurring to an optimization of HVAC management and thermal storage exploitation [129]. Smart energy management at the district scale can also be obtained also considering district heating networks and industrial waste heat recovery [130,131]. Several studies are dealing with the impact of solar collectors and photovoltaic systems in emerging countries The recent growth in energy prices and the new technologies available lead to new market mechanisms such peer-to-peer trading among prosumers [132–134]. New techniques have been applied in recent years also to produce more reliable energy models, crucial to ensure reliable evaluations of the energy efficiency measures proposed [135]. Traditional techniques such as regression models [136,137], change-point process [138] can be nowadays overcome recurring to novel probabilistic models [139], deep machine learning [140,141] and artificial neural networks [142].

3.3. Structural issues and seismic performance

As previously mentioned, the Emilia Romagna earthquake in Italy in 2012 brought attention to the structural behaviour of precast industrial facilities, producing a growing interest toward the theme in the scientific community. Research discussing the structural and seismic performance of industrial buildings started to be widely diffused in literature and is still very common nowadays, with a series ofmultiple subtopics as addressed andhighlighted in Fig. 10.

The majority of studies focus on vulnerability analyses and loss assessment studies that coveri 33 % of the publications. The related contributions are listed in Table 6.

Only a few of the studies deal with steel structure facilities [143,147,164] or cast-in-place reinforced concrete buildings [156,163].

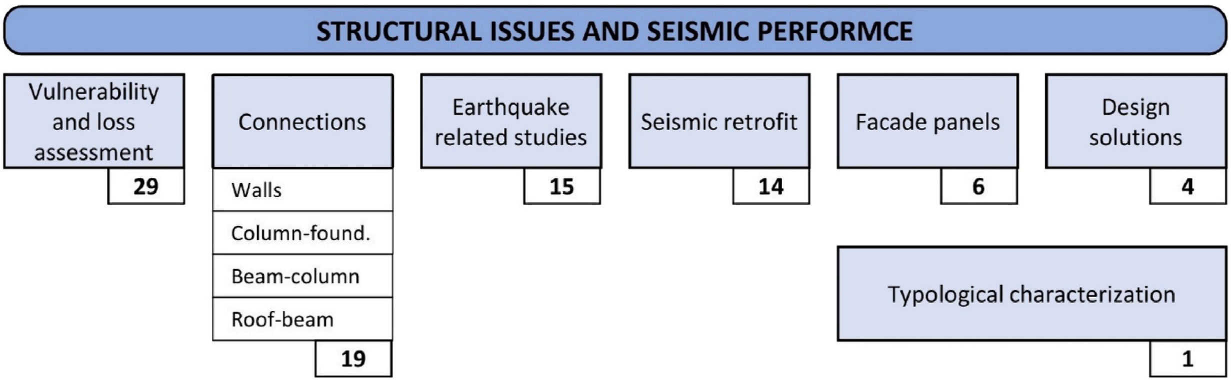

Fig. 10. Structural issues and seismic performance related publications: subtopics and number of studies.

Most of the research available is based on the Italian scenario [144,146,148–152,154,155,157,162,163,165,170], followed by Turkey [143,153,158–160,166,167,169] and Portugal [145,168,171]. To cover a representative amount of possible building configurations, several studies offer a preliminary overview of the national or regional building stocks considered providing a typological classification [144,145,148,150–152,157,158,161,165–169,171,172]. Some representative case studies are usually addressed to extract relevant structural parameters and characteristics to be used in numerical simulations or to validate their results.

The literature extensively covers post-earthquake investigation of industrial buildings in different countries such as China [173,174], Chile [175,176], and Italy. The latter proved to be the most addressed one, accounting for 2/3 of the literature. Del Gaudio et al. propose a comprehensive review of the past main seismic events and the related damage scenarios [177], while the other studies available focus on the consequences of the Emilia Romagna earthquake in 2012 on both historical manufacturing buildings [178] and precast concrete structures [179–186]. As highlighted by Batalha et al. [187] reviewing the findings of the previously cited research, precast reinforced concrete industrial buildings are exposed to severe failures in both structural and non-structural elements: short-column effects, connections' failures, rocking and detachment of the external cladding panels are the most recurrent phenomena. Structural connections are thoroughly analysed considering the beam-to-column [188–197] roof-to-beam [198–200], column-to-foundation [201,202] and walls-to-structure [203–206] connections. External walls are examined in literature considering steel [207] and precast structures, including in this case reinforced masonry infills [208,209] or precast cladding panels installed both in horizontal [210,211] and vertical direction [212].

Despite the deficiencies currently affecting industrial buildings, their structural retrofit has to be preferred over their demolition and reconstruction within a life cycle perspective as suggested by Raposo et al. [213]. Different seismic retrofit options are available and discussed in the literature, mainly addressing precast facilities while only one paper deals with steel frame structures [214]. Most of the studies evaluate the installation of dissipative braces or beam-to-column friction connection devices [215–220]. Other studies explore the introduction of shear walls [221], rigidity elements [222] or an external exoskeleton [223]. The reinforcement of the existing precast columns with steel jacketing installation is evaluated by other authors along with a comprehensive comparison of different retrofit alternatives including interventions on connections and external cladding [224–226]. Additionally, publications concerning novel [227–229] or optimized design solutions [230] can be also retraced.

4. Conclusions

The review presented in the paper was performed adopting the PRISMA methodology to point out the publications of interest. Specific keywords, research queries, filtering and exclusion criteria were set within the framework of a systematic methodological approach and applied to two widely recognised scientific online databases. The searching phase resulted in the selection of 203 publications about industrial buildings and a wide range of topics were identified. A preliminary computer aided bibliometric analysis was conducted using VOSviewer to produce visual maps for keywords and terms occurrence analysis. Based on the evidence of this preliminary stage, a manually performed review was consequently performed by the author proposing a classification of the publications retrieved. In Fig. 11, the main findings of review are synthesized, presenting the share of each topic with respect to the total amount of studies and to the relative cluster.

The main findings obtained following the extensive review performed can be synthesized as it follows.

- Bibliometric reviews proved to be an effective preliminary research tool to manage a considerable amount of publications and to autonomously sort them. However, when a large set of terms is considered, some unclear principles seemed to be applied during the clustering operations.
- Industrial buildings are still not a widely discussed topic in the scientific panorama. A certain growth of interest was registered during the last years especially considering building performance or energy related features that can be considered an emerging field of research. On the other hand, the inadequate structural behaviour of concrete precast industrial facilities became is more frequently addressed in the literature following the seismic events occurred in Italy in 2012.
- The energy demand associated with heating, cooling, and lighting operations is frequently neglected in discussions on energy efficiency measures for industries, despite literature demonstrating that these demands can be comparable in magnitude to production activities.
- Several uncertainties affect the estimation of the operational energy demand in industrial buildings. At first, determining the exact amount of external air infiltration is particularly challenging in these facilities, where air-tightness is often compromised by poor maintenance conditions. Specifying internal heat gains enhances the quality and reliability of energy building simulation procedures for industrial buildings, as machinery related thermal loads can significantly impact the overall non-process energy demand. Given the great influence that local factors have on the overall behaviour of existing industrial buildings, generalized considerations can be hardly formulated starting from single publications. A comprehensive review is hence required to provide a general overview of the different topics allowing to go beyond the limits of specific case-study oriented studies.
- Retrofit solutions are generally analysed focusing on singular building components or targeting only structural, architectural, technological or energy aspects. A multidisciplinary approach is usually missing except for a very limited amount of studies.
- Studies on envelope refurbishment generally explore the enhancement of thermal insulation properties, the substitution of skylights and glazed portions or the implementation of cool roof solutions.
- Redevelopment of heating, cooling and lighting solutions is considered preferrable over interventions focused on improving envelope performance also because of its cost-effectiveness. At the same time maintaining proper internal air temperature and distribution, as well as ventilation requirements, is fundamental to ensuring indoor conditions and preserving worker well-being. The

Table 6
List of papers about vulnerability analysis and loss assessment. For each study the publication year, the reference country and the construction technology examined are reported. The approach adopted in the study is also included by specifying if a classification of the industrial building stock is provided, if a case study facility is addressed or if an ideal hipotetical one is considered.

Reference	Year	Country	Structural material	Study approach		
				Classification	Case study	Ideal building
[143]	2011	Turkey	Steel		X	
[144]	2016	Italy	Precast RC	X		
[145]	2022	Portugal	Precast RC	X		
[146]	2017	Italy	Precast RC	X		
[147]	2017	n.a.	Steel			X
[148]	2019	Italy	Precast RC	X	X	
[149]	2021	Italy	Precast RC		X	
[150]	2015	Italy	Precast RC	X		
[151]	2014	Italy	Precast RC	X		
[152]	2017	Italy	Precast RC	X		
[153]	2022	Turkey	Precast RC		X	
[154]	2018	Italy	Precast RC		X	
[155]	2019	Italy	Precast RC		X	
[156]	2020	Thailand	RC		X	
[157]	2019	Italy	Precast RC	X		
[158]	2017	Turkey	Precast RC	X		
[159]	2019	Turkey	Precast RC			X
[160]	2019	Turkey	Precast RC			X
[161]	2018	Ukraine	Steel	X		
[162]	2016	Italy	Precast RC		X	
[163]	2020	Italy	RC		X	
[164]	2020	n.a.	Steel	X		
[165]	2018	Italy	Precast RC	X		
[166]	2010	Turkey	Precast RC	X		
[167]	2014	Turkey	Precast RC	X		
[168]	2022	Portugal	Precast RC	X		
[169]	2021	Turkey	Precast RC	X		
[170]	2017	Italy	Precast RC		X	

implementation of heat recovery units, smart control, and management solutions are pointed out as highly beneficial as well as the installation of high efficiency heating generators or heat pumps. To prevent summer overheating, passive solutions can be deployed relying on enhanced natural ventilation and free cooling. Otherwise evaporative cooling system are considered as promising solutions but unsuitable in a strictly controlled environment since their operation is highly dependent on external conditions, making dehumidification processes impossible.

- The vast internal area of industrial buildings, coupled with the limited number of openings typically found in the external envelope, can result in a substantial energy demand to maintain appropriate lighting conditions in working areas as recognised in several study. In this case, both acting on skylights and windows and replacing the existing lighting devices with LED ones is analysed.
- Solar radiation for thermal or electric energy production is addressed as the most promising option for integrating energy from renewables industrial buildings due to its architectural integration feasibility. To enhance their exploitation, storage devices should be implemented but are still not widely adopted because of the high costs connected. At the same time, shared energy consumptions via microgrids or economic compensation models can be profitable for industrial settlements. Research should be deepened in this direction because the few studies available are not sufficient to provide an exhaustive knowledge of this topic.
- Power metering and management information systems are crucial decision tools for identifying optimal strategies in energy use, achieving cost reductions, and simultaneously reducing carbon footprint. Regularly training artificial intelligence-based tools with real data on power and energy consumption proved to be effective in energy forecasting and identifying consumption spikes.
- Given the peculiarities of industrial buildings, the implementation of commonly adopted sustainable building rating approaches may yield inaccurate results or misleading environmental performance assessments in manufacturing facilities. Similarly, when considering the redevelopment strategies to be applied on industrial buildings, greater importance to qualitative variables (e.g., flexibility, reliability) and initial financial investments should be applied when compared to other intended uses.

CRediT authorship contribution statement

Neri Banti: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization.

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.

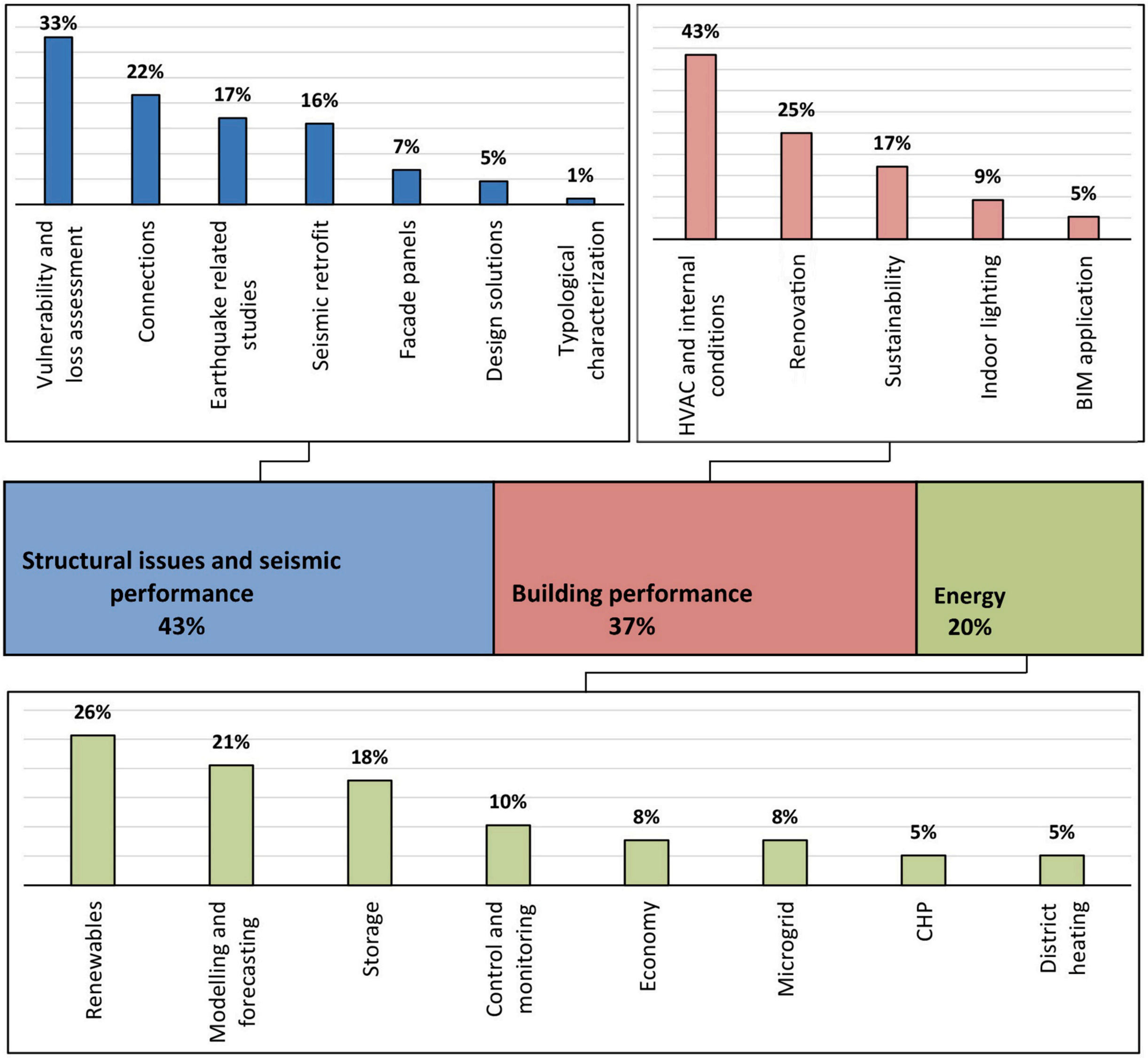

Fig. 11. General overview of research about industrial buildings currently available in the literature. The three main research areas and their share in the literature are reported. The subtopics identified and referrable to each of them are also specified.

Data availability

No data was used for the research described in the article.

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