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Review article

Identification of methodologies to quantify education system resilience—A scoping review

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ABSTRACT

Schools and other educational institutions are important for the well-being of society. However, education continuity is increasingly threatened by negative influences such as disasters and acts of violence. An important tool to ensure the safety of educational institutions is the development of a methodology to measure education system resilience. To advance the development of such a methodology, a scoping review is conducted to identify current quantification methodologies for education system resilience and to highlight promising research directions. The procedure of the scoping review is developed following the specifications of Joanna Briggs Institute Reviewer's Manual in accordance with the PRISMA-ScR-checklist. Quantitative psychological approaches are excluded for reasons of consistency of the resilience conceptualization. Resulting from a total of 2528 records, 31 are involved in data synthesis comprising (case) studies from the continents of Asia, North and South America, as well as Europe. While the scoping review started broad, a predominance of building-related studies and natural hazards was identified. Furthermore, the methodologies mainly differ along three dimensions: scope, level of detail, and complexity. However, no methodology achieves high performance on all dimensions. Altogether, it can be recognized that all methodologies possess individual advantages that complement each other well. Therefore, a framework for combining the different quantification methodologies is proposed to achieve the most accurate and comprehensive quantification possible. Considering only limited available resources, an adaptation of the proposed methodology to the educational institution's and its community's social, geographic, and further circumstances is essential to allow for a prioritization of quantification components.

1. Introduction

Schools and other educational institutions are essential for the well-being of society [1,2]. They can improve risk perception and reduce disaster impacts [3,4] by providing continuous education on Disaster Risk Reduction (DRR) [5,6]. Furthermore, schools are regularly used as evacuation shelters [7] and community meeting places [8]. This stabilizing function is especially important for children, who exhibit a particularly high vulnerability and susceptibility to disasters and education disruption as a consequence [9]. An increase in the number and intensification of disasters can be observed, related to both natural [10] and anthropogenic

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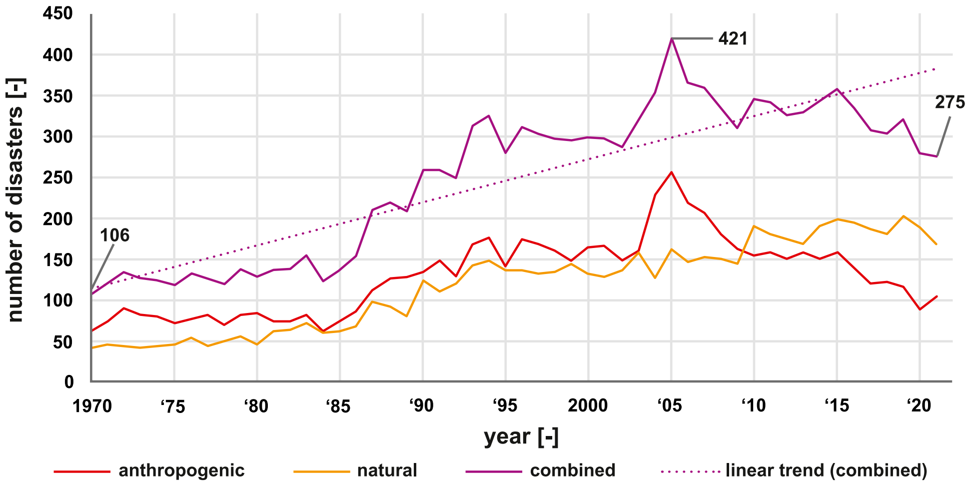

Fig. 1. Number of disasters recorded per year from 1970 to 2021.
Source: [14], own presentation.

hazards [11,12]. Fig. 1 illustrates this trend using the latest Swiss Reinsurance Company (Swiss Re) data. The data do not refer to a specific sector but encompass all reported catastrophes on a global scale. By Swiss Re definition, natural catastrophes include floods, storms, earthquakes, droughts/forest fires/heat waves, cold waves/frost, hail, tsunamis, and others, while man-made disasters comprise major fires and explosions, aviation and space disasters, shipping disasters, rail disasters, mining accidents, the collapse of buildings/bridges, and miscellaneous including terrorism, but excluding war, civil war, and war-like events [13]. Within this definition, however, it is emphasized that anthropogenic influences do take on an important part in all incidents described as natural catastrophes as well [13].

Climate change impacts and other anthropogenic influences will continue to increase the overall number and intensity of disasters[1] in the future [19], as illustrated in Fig. 1 (linear trend). Therefore, among other infrastructures, educational institutions are persistently exposed to various risks and hazards, as highlighted by Yusuf et al. [20] and Mirzaei et al. [21], which jeopardize their operations and pose a constant threat to education continuity. On a global scale, school buildings are regularly destroyed by disasters [22] and education is disrupted by acts of violence [23]. The most common types of disasters that have negative impacts on schools and the surrounding school community include landslides and earthquakes, heat waves, and droughts, floods, storms such as typhoons, cyclones, and hurricanes, or tsunamis [24–26]. On top of the direct injuries and fatalities among students, teachers, and others involved [27] particularly the destruction of school buildings leads to multiple consequential impacts such as a significant infringement on the right to education as Segarra-Alméstica et al. [28] report a negative educational outcome after disasters resulting in education disruption. Besides that, even social disruption can be a consequence of disasters, such as tornadoes, impacting education continuity [29]. Additionally, the education sector was one of the areas most affected during the COVID-19 pandemic [30] and experienced significant disruptions [31,32]. Globally, schools were compelled to close for extended periods, leading to a shift towards online education [33]. However, this sudden transition to remote learning posed challenges and disadvantages, especially for students without access to digital devices or insufficient parental support [34,35]. While the long-term consequences cannot yet be comprehensively and accurately anticipated, there are indications that the negative effects of distance learning may extend far into the future [36,37]. This can be attributed, inter alia, to the extension of learning gaps [38] that can arise from the constrained capacity of parents to support their children during distance learning periods, particularly in low-income households [39]. Moreover, students exhibit the highest level of stress in the aftermath of transitioning between face-to-face and distance learning, contrary to other stakeholders such as parents, teachers, or principals [40]. Beyond the academic aspect, the closures and associated contact restrictions had adverse effects on students' social interactions [41,42], and there is empirical evidence linking the limited functioning of the education system to negative consequences on the mental and physical health of young individuals [43–46]. In the restructuring of daily life necessary to cope with COVID-19 restrictions [47], family-related problems emerged as a primary concern, as opposed to problems with friends and peers or school-related difficulties, and youth exposed to prolonged school closures faced these challenges more intensely and over a longer period of time [48].

For all of these reasons and disruptive events, it is essential to prioritize the protection and preparedness of schools against potential future disasters [49]. To achieve this goal, several developments and advancements are needed [50,51]. One essential

[1] Considering the ongoing controversy surrounding the term 'natural disaster' [15], current research indicates that disasters can never be solely natural but arise from the mutual interaction between natural hazards and social structures [16]. They result from human systems' inability to effectively address the intricate relationships and interactions between societal vulnerability and environmental factors [17]. Therefore, as suggested by Chmutina and von Meding [18], the sole term disaster is used, and the underlying factors for a particular scenario are discussed, if necessary.

tool is a methodology to measure and compare education system resilience (ESR) [52]. Two main difficulties can be identified with regard to the development of such a methodology: First, it must be adapted to the specific social and geographical circumstances of the institutions and surrounding school communities considered [53]. And second, it should be as comprehensive as possible to accurately portray complete and correct results [5].

A growing number of approaches are available to improve the resilience of schools. Commonly, this is attempted by trying to increase the resilience of schools or educational institutions in general. A conceptual framework addressing the most important factors for increasing the resilience of educational institutions has been developed by the Global Alliance for Disaster Risk Reduction & Resilience in the Education Sector (GADRRRES) (cf. [51]). However, this is strictly qualitative and provides no means of quantification. Furthermore, some approaches address individual disasters and adopt a less comprehensive perspective. Available literature focuses primarily on natural hazards such as earthquakes or floods. However, fires or threats on the way to school are also highly relevant [54]. As this area of research is continuously growing and becoming more widely recognized, a significant increase in the number of publications in recent years can also be observed. Among these, the use of indices to reflect the resilience of educational institutions can be identified as a key approach. Exemplary applications can be found in Mirzaei et al. [5], Shah et al. [55] and Tong et al. [56]. At this point, the quantification of these indices, in general, is not yet very sophisticated and is based on qualitative or semi-quantitative expert assessments, for instance, using 5-point Likert scales. However, a few rather complex approaches exist that use more advanced methodologies, such as Bayesian networks (cf. [57]). In adjacent research areas (for example, in DRR or Critical Infrastructure as well as community resilience), robust scientific bodies for the quantification of resilience may already exist [58], but they are still recognized as in need of further research nonetheless [59]. Overall, education system resilience is still among the least-studied components in the quantitative disaster literature [60]. When considering education system resilience, especially the co-existence of qualitative and quantitative indicators as well as their interdependent relationship with societal or community resilience pose particular challenges to quantification. Altogether, a few different approaches exist to quantify education system resilience. Nevertheless, there appears to be no fully developed methodology that can be used as a framework for ESR quantification. To support the development of a comprehensive and advanced quantification methodology, it is necessary to understand what approaches have already been addressed, what advantages and disadvantages exist, and what further research opportunities can be identified. Therefore, the goal of this article is to conduct a scoping review on existing methodologies that quantitatively analyze education system resilience and include any empirical or quantitative data processing techniques posing three research questions:

Research questions

- Which methodologies for the quantification of ESR can be identified?
- What are their advantages and disadvantages?
- Where are current limitations and research gaps or desiderata?

These research questions require a prior delineation of education system components and the applied definition of resilience as this significantly impacts the nature and scope of resilience indicators [61]. Therefore, to identify as many relevant facets of quantification methodologies as possible, this definition needs to be determined prior to conducting the scoping review: No general definition of resilience has yet been developed, as it depends on the particular discipline or research area it is used in [62]. Although the scientific literature describing resilience is of such a wide scope that it can hardly be summarized [63], it is nevertheless possible to identify various dimensions and characteristics in the individual disciplines, which can be influenced by at least 30 accompanying terms (cf. [62]) (for an overview of different disciplines, the term resilience is used in, see Alexander [63]). Engineering or technical resilience describes the ability of a system to recover to its original state after the impact of disruptions and is measured as a function of time [64,65]. It thus describes a reactive component of resilience [66] and is mostly applied to systems with a single equilibrium [67]. Due to these systems' limitations [67] another approach for systems with more than one equilibrium exists, for example, in ecology to describe the interactions between populations of different animal species as a function of environmental influences (such as temperature and humidity) [68]. This (extended) ecological approach understands resilience as the ability of a system to absorb disturbances or withstand them while maintaining its basic structures until it adapts to the new condition and transitions to a new equilibrium [69]. However, when considering complex adaptive systems (such as education systems and communities or modern urban infrastructures), resilience no longer solely describes the transition to an old or new equilibrium, but rather the continuous adaptation to changing circumstances [62]. Additionally, Bosher (2014) recognizes the need for an anticipatory component as this shifts the focus of continuous adaptation from a reactive to a proactive approach.

Therefore, to capture as many facets of ESR as possible, education system resilience is, in accordance with the concept of functional resilience (cf. [70,71]), defined as the capacity of an education system to absorb, resist, and adapt to disturbances while ensuring the continuity of its vital functions. The concept of ESR encompasses multiple dimensions and goes beyond recovering to a previous state or new equilibrium but extends to continuous adaptation and proactive anticipation of changing circumstances. Especially, due to the interdependent relationship of ESR with community or societal resilience (CSR) or urban resilience, many different components are to be considered that impact ESR. These comprise, for instance:

- structural resilience (of school premises, structures, equipment) [72],
- the resilience of underlying or support structures (emergency response services, public authorities) [73],

- psychological or mental health resilience (of teachers, students, etc.) [74], and
- the resilience of complex systems influencing ESR (critical infrastructures, political bodies, etc.) [75,76].

Furthermore, continuously greater focus is placed on the connection between resilience and the whole-of-society approach [77]. Therefore, as education system resilience is closely connected to community and societal resilience and positively impacts CSR [78], it is necessary to include these quantification approaches in the review as well, at least to some extent. Especially because there are many quantification options for CSR, but they have yet to be put into practice [58]. Altogether, the field of education system resilience is far too comprehensive to be covered entirely with a single review and the selection of the dimensions and components to be included is not trivial. An as exact as possible outline is developed in conjunction with the methodology for scoping reviews (definition and application of eligibility criteria) adopted in this article.

2. Concept and methodology

A scoping review will be performed to map the key concepts of a research area [79]. At this stage, the aim is to identify the various concepts and methodologies already in existence for quantifying ESR and to gain an overview of which is most suitable or what the advantages and disadvantages are, and where there is a need for further research. Therefore, conducting a scoping review is very well-suited. Scoping reviews are well described in scientific literature, and several instructions exist on conducting them. The procedure of the scoping review follows the specifications of Joanna Briggs Institute (JBI) Reviewer's Manual (cf. [80,81]), which is oriented on Levac et al. [82] and Arksey and O'Malley [79]. To further guide the elaboration, the PRISMA-ScR-checklist is used to guarantee that all necessary items are being considered and to limit reporting bias [83]. This checklist is an extension of the PRISMA statement in congruence with the JBI manual [80]. A concise outline of the methodology is illustrated in Fig. 2. For an in-depth consideration of every checklist item, please consult the review protocol accompanying this article.[2]

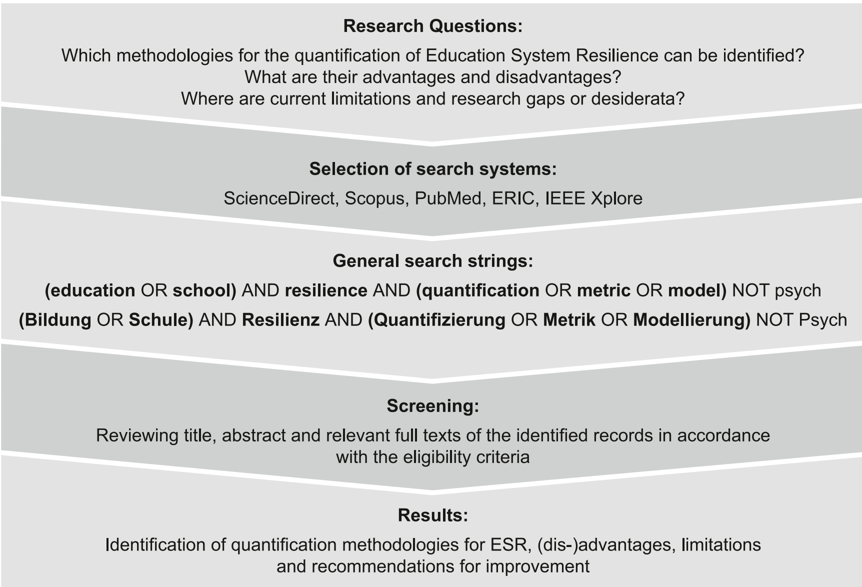

Fig. 2. Summary of the procedure of searching for, identifying and screening relevant articles.

Concept: To achieve an as comprehensive as possible overview of the quantification methodologies for ESR, several requirements must be considered. As the field of ESR quantification is one of the least studied areas in disaster literature [60] and the need for further research is evident [52], it cannot be expected to retrieve a sufficient result from reviewing the research area with a too narrow design. This results in three essential inclusion criteria:

Reflecting the definition of ESR adopted in this article, publications that (partially) address these dimensions will be included in the scoping review:

- resistance to disturbances,
- absorption of impacts while maintaining basic functions,
- recovery to an original state or new equilibrium after a disruption,

[2] https://www.researchgate.net/publication/373581427_Scoping_Review_Protocol_Identification_of_Methodologies_to_Quantify_Education_System_Resilience

- continuous adaptation to changing circumstances, and
- an anticipatory element that can be used to react, anticipate and act in advance.

Furthermore, the review is conducted on a global level to gain access to as many relevant publications as possible, although it might be more difficult to compare the methodologies because of different underlying influences such as cultural factors, geographic locations, and social interests [21]. Additionally, to expand the consideration to a more holistic understanding of which suitable quantification methodologies exist for ESR, the adjacent research area of CSR is also considered because of the similarities and interdependencies these areas share [84]. However, respective quantification methodologies can only be deemed relevant if they inherit a connection to ESR specifically and address the inherent properties and challenges. As an example, the study by Parajuli et al. [6] is included because it considers CSR in conjunction with educational communities and focuses on the education sector as well as its influence on CSR. In contrast, the study by Cutter et al. [85] has no specific perspective on ESR, although the disaster resilience index therein comprises educational equity and thus does include the education system in general but does not address ESR in particular.

A further limitation is made for the areas of the education sector considered. Due to the large differences between the individual levels (from daycare to higher education), it must be assumed that different dimensions and criteria can have a diverging influence on the different levels. Therefore, this study will focus on a subset that partially encompasses the primary and secondary sectors of the education system: primary and secondary schools. The review will not include publications focusing on kindergartens, daycare centers, vocational schools, colleges, and universities.

Moreover, a few restrictions must be made to limit the search to the most important factors: Only publications including explicit quantitative methodologies are considered. This is important because some studies focus on developing qualitative indices for ESR by identifying the relevant indicators without quantification (cf. [86]). Since this article explicitly aims to identify quantification methodologies, these approaches cannot be included even when addressing ESR at its core. Besides that, although the psychological resilience of students, teachers, and others involved in the education system is an important part of ESR [9], it is excluded from the review because the underlying concept of resilience differs significantly, which would further complicate the review and, additionally, this research area often focuses on student academic performances [87] in contrast to the fundamental concept of education continuity addressed in this review.

Considering that relevant techniques or methodologies could be found in scientific literature and more practice-oriented publications, the search must be extended to both domains. Thus, on the one hand, peer-reviewed journal articles and peer-reviewed conference papers are included. On the other hand, gray literature such as theses, textbooks, or publications of academic societies will also be searched. Additionally, both English and German will be eligible.

Search strategy: The information sources are limited to search systems such as literature databases. Relevant search systems or databases were identified by several criteria: On the one hand, search systems recommended by Gusenbauer and Haddaway [88] were considered. Due to unrestricted access three search systems were selected: ScienceDirect, Scopus, and PubMed. On the other hand, the Education Resources Information Center (ERIC) and IEEE Xplore were included as subject-specific databases providing education research and information as well as an engineering and computer science background to address quantification methodologies specifically. The elaboration of a search strategy was designed following the specifications of the JBI Reviewer's Manual. Initially, an orienting literature search with the search systems Google Scholar, ScienceDirect, and ERIC was performed. Based on this, relevant publications could be determined and consulted to identify further literature. From these publications, a list of synonyms of the original search terms was created and extended using online thesauri to guarantee as thorough a search as possible. From this, the final search strings were constructed:

Final search strings

- (**education** OR **school**) AND **resilience** AND (**quantification** OR **metric** OR **model**) NOT psych
- (**Bildung** OR **Schule**) AND **Resilienz** AND (**Quantifizierung** OR **Metrik** OR **Modellierung**) NOT Psych

These were then customized to the databases by applying the individual characteristics (such as the use of wild cards and the availability of data fields). The final search strings for both English and German are appended in the review protocol.

Data items: The variables for which data were collected are oriented on the objectives and the research questions. The main objective was to identify and differentiate various methodologies to quantify ESR. Therefore, the type of methodology was considered as a first step. Examples include mathematical models, simulations with Agent-based Modeling, and Digital Twins, or Geographic Information Systems. Besides that, the original publications' advantages and disadvantages, identified by the authors, were extracted. Additionally, limitations and recommendations for further development of the quantitative methodologies were listed. It is important to mention that the data items were only applied to the quantification methodology. Therefore, no discussion will be raised about which indicators are better suited to represent ESR or what advantages may arise from stronger political support and a higher budget in a specific setting, for example. Accordingly, the data items in the calibrated forms (see supplementary material) relate exclusively to the methodology, as this is the scope of the study. Although it can be assumed that every peer-reviewed journal article contains all data items in general, if the calibrated forms contain the phrase 'none specified', this solely indicates that the respective data items are not available for the quantification methodology.

3. Results

The literature search was performed from November 13th 2022 to November 17th 2022 and resulted in 2515 records that had to be processed initially. Table 1 provides the exact output of every search system. Despite using the same search string (along with a customized search syntax), there were notable variations in the records retrieved by the search systems. In addition, ERIC and IEEE Xplore, which were chosen to obtain results from a specific research field, retrieved substantially fewer records compared to the other search systems. Moreover, the search was able to identify a mere 45 German-language publications.

Table 1
Number of records output by the individual search systems.

Language	ScienceDirect	Scopus	PubMed	ERIC	IEEE Xplore	Total
English	391	1792	219	18	50	2470
German	41	0	0	0	4	45
Total	432	1792	219	18	54	2515

Fig. 3 depicts the literature search and selection process, which involved identifying 2515 potentially relevant records by applying the developed search strings. Additionally, 13 publications were identified through other sources. Of the total number of records, 265 (10.48%) were duplicates, while 46 (1.82%) did not have an abstract and were thus removed. After title and abstract screening, 44 (1.98%) of the remaining 2217 records were identified as potentially relevant for data synthesis. However, due to access restrictions, 5 (11.36%) of these 44 records had to be excluded from further investigation. Following a full-text screening of the remaining publications (39) and those added based on references (8) using the eligibility criteria, 31 (65.96%) publications were identified as relevant for data synthesis. In summary, out of the initial 2528 records, only 31 (1.23%) were included in the data synthesis (a list comprising all included publications is provided with the supplementary material).

All included publications have been published since 2012, even though there was no specific limit or restriction on the publication date. 14 (45.16%) of these publications deal with the seismic resilience of school buildings, 5 (16.13%) with thermal energy and heat waves, 1 (3.23%) with air contamination, 4 (12.9%) with the school buildings' resilience against typhoons and tornadoes, and 1 (3.23%) with resilience to flood disasters. 4 (12.9%) use a multi-hazard approach considering more than two disaster types and 4 (12.9%) intend an as comprehensive as possible perspective.[3] Furthermore, 16 (51.61%) publications address ESR quantification performing case studies in Asia, 7 (22.58%) in Europe, 6 (19.35%) in North America, and 2 (6.45%) in South America (as illustrated by the world map in the supplementary material). No publications were obtained that address case studies in Africa or Australia. 21 (67.74%) studies apply quantification methodologies based on mathematical models without using other techniques. These range from simple linear models to more complex ones such as exponential, probabilistic and numerical models. Beyond that, 1 (3.23%) employs GIS tools, while 1 (3.23%) uses agent-based modeling, 1 (3.23%) utilizes artificial intelligence (neural networks), and 7 (22.58%) apply field-specific simulation software. A composite summary of the use of quantification methodologies along with the considered disaster types is displayed in Table 2.

Table 2
Classification of the individual publications according to the applied methodologies as well as the investigated disaster types.

Methodology		Seismic	Thermal energy	Air contamination	Wind storms	Floods	Multi-hazard	Comprehensive
Mathematical models	Numerical	6, 12, 13, 18, 22, 30, 31	–	–	2, 29	–	7, 8, 11, 28	–
	Linear	3, 4, 5, 6, 9, 10, 12, 13, 16, 18, 21, 22, 30, 31	4, 14, 15, 17, 26	15	1, 2, 19, 29	24	7, 8, 11, 28	20, 23, 25, 27
	Exponential	3, 4, 5, 6, 10, 12, 13, 16, 18, 22, 30, 31	4, 14, 17	–	1, 19, 29	–	7, 8, 11, 28	–
	Probabilistic	3, 5, 6, 10, 13, 16, 30, 31	–	–	1, 2, 19, 29	–	7, 8, 11, 28	–
AI	Neural networks	5	–	–	–	–	–	–
GIS tools		3	–	–	–	–	–	–
Simulations	Field-specific Simulation Software	18, 21, 22	14, 15, 17, 26	15	–	–	–	–
	Agent-based Modeling	–	–	–	2	–	–	–

The numbers in this table correspond to the sequential numbers assigned to the publications included in data synthesis (see supplementary material).

[3] total sum greater than 31, since publications addressing several disaster types were counted more than once

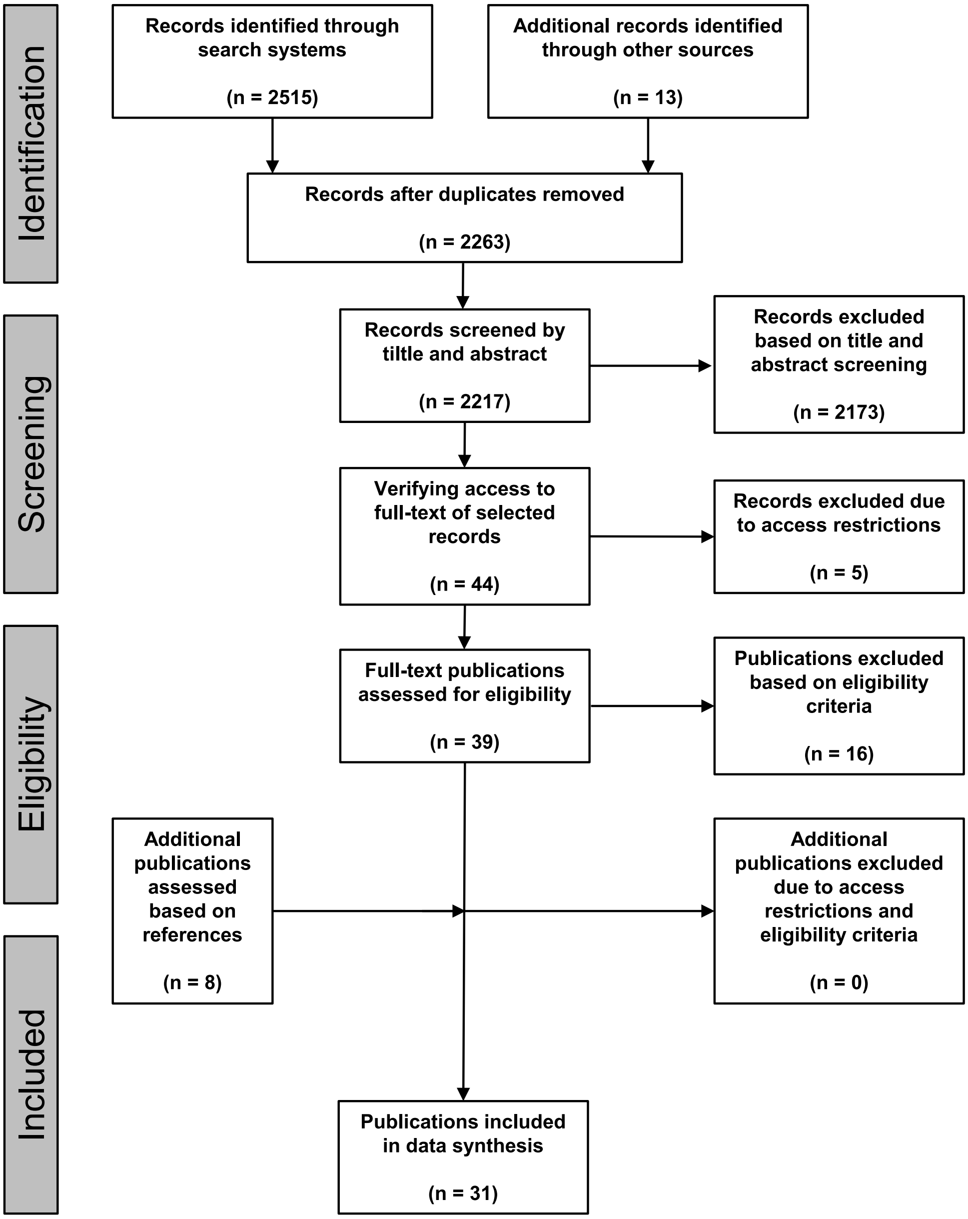

Fig. 3. Adapted PRISMA flow chart illustrating the number of processed records per individual review step.
Source: [83], own presentation.

4. Discussion

Various approaches to quantify ESR as well as dis-/advantages, limitations and research gaps could be identified. These address different aspects or dimensions of resilience and can be divided into two basic approaches: low-dimensional studies that consider only one or at most two hazards separately and multi-dimensional studies that consider a variety of hazards collectively or even adopt a comprehensive approach. It can be recognized that no identical taxonomy of resilience exists. For example, most studies quantifying seismic resilience approach this goal by measuring a building's seismic vulnerability from which resilience can be derived. Furthermore, some multi-hazard approaches combine resilience and risk assessments to identify the most vulnerable parts of the considered objects (e.g., buildings). However, although the orientations or baseline frameworks may differ, all studies ultimately share the same objective of providing a measure for resilience. Nevertheless, this fact demonstrates that quantifying resilience is a complex problem that cannot be easily solved.

The results of the scoping review reveal that building-related studies and natural hazards predominate among the considered publications, with nearly half of all eligible studies addressing earthquakes specifically. This pattern and frequent coverage is not at all surprising, since earthquakes occur in numerous locations and cause many deaths and injuries to school members as well as destruction of school buildings [25]. These impacts greatly affect the functioning and efficiency of education systems as temporary school buildings may have to be established to secure a state of education continuity and students as well as others involved can suffer extensive psychological traumas such as Post-Traumatic Stress Disorder [89]. After some particularly devastating events, such as the earthquakes that occurred as recently as February 2023 in Turkey and Syria, education continuity may not be possible at all, either because the educational facilities are too badly damaged, or those affected are forced to relocate as their homes are destroyed, which can further complicate education through socio-cultural barriers [90]. Furthermore, the absence of essential infrastructure and vital resources like electricity and water can pose challenges for both the education system and students in effectively providing and pursuing education [91]. Although the other disaster types are not as frequently addressed as earthquakes, their destructive potency is equally significant and they are triggers for numerous casualties and disrupted infrastructure as well [92].

Although there are regular reports of anthropogenic disasters with regard to education systems, such as terrorism, student abductions, school shootings, or armed conflicts, that negatively impact educational institutions and the surrounding community [93,94], no study has been classified as eligible that addresses these issues. The dominance of natural hazards and building-related studies may be explained by the fact that psychological resilience aspects were excluded from the consideration. As Makwana [95] indicate that PTSD is more often triggered by anthropogenic events rather than by natural hazards-related disasters, it seems plausible that anthropogenic disasters are less likely to appear in the scoping review results. Additionally, natural hazards-related disasters, in general, create the most negative impact on the welfare of countries, their inhabitants, and economies [96]. Although the impacts do vary greatly depending on country size and wealth, this could focus greater scientific attention on natural hazards and related disasters.

4.1. Low-dimensional approaches to ESR quantification

The low-dimensional approaches in this study can be categorized based on the specific disaster types they address. Through an analysis of the literature, five primary disaster types have been identified: **seismic events** (e.g., earthquakes), **thermal energy** events (e.g., heat waves and energy efficiency of school buildings), **air contamination**, **floods**, and **wind storms** (see Table 2). To enhance clarity and comprehension, the discussion is organized according to these disaster types. Since thermal energy and air contamination are closely intertwined in the literature, they are discussed jointly.

4.1.1. Seismic resilience

The concept of seismic resilience has lately gained increased attention [97] and has experienced vast progress and development, especially concerning the retrofit of school buildings and the concept of 'building back better' [98]. Due to the many new insights and different approaches, a World Bank initiative (GPSS[4]) was developed to strengthen the safety of schools against seismic events as well as to expand and harmonize the knowledge of researchers and practitioners involved (e.g., uniform terminology) on an international level through a global library of school infrastructure (GLOSI) [49]. There are many different methodologies to measure the resilience of school buildings to seismic events [99]. The most commonly used approaches are vulnerability, fragility, and recovery functions. While fragility functions indicate the probability that a building will be damaged based on the intensity of the seismic event expressed by measures such as peak ground acceleration [100], vulnerability functions relate the intensity to the structural loss of the building [101]. Yin et al. [102], Anelli et al. [103] and Yamin et al. [104] use vulnerability functions while Carofilis Gallo et al. [97], Chalabi et al. [105], Giordano et al. [106,107], Hassan et al. [1] and Cimellaro et al. [108] use fragility functions. In contrast, Yin et al. [102], Fu et al. [109] and Eghbali et al. [110] use functionality or recovery functions that express the recovery times of buildings after earthquakes and their degree of recovery. These functions are most commonly derived from expert opinions, empirical data, or analytic/numeric simulations [106]: Giordano et al. [106], Yamin et al. [104], Marasco et al. [111], Noori et al. [112] and Cimellaro et al. [108] achieved the required data by applying Monte Carlo simulations, Chalabi et al. [105], Yin et al. [102] and Yamin et al. [104] used Incremental Dynamic Analysis (IDA) and Carofilis Gallo et al. [97] calculate the functions with a software specifically designed for probabilistic seismic hazard analysis. These approaches represent the more conventional and established methodologies well researched and recognized internationally. Giordano et al. [107] use a novel mechanical-based closed-form solution for the out-of-plane seismic assessment of masonry school buildings in combination with a modified version of the Capacity-Spectrum-Method that can be used to evaluate building responses under earthquakes and plots acceleration versus building displacement [113,114]. Additionally, different studies utilize approaches such as calculating damage ratios based on various building performance measures [109] or Dynamic Building Simulation software [111,112,115]. Besides, there is one study [105] that uses artificial intelligence (neural networks) to achieve quantification and one that integrates various GIS tools in its elaboration [103]. With a few exceptions, these methodologies use more or less simple mathematical models that can be handled and applied by most engineering graduates [49]. However, some approaches that combine many mathematical models with more advanced techniques to approximate a best-case scenario are described as very complex [97]. Moreover, the underlying measures or indicators differ, so the methodologies vary slightly. For example, Carofilis Gallo et al. [97] consider economic losses, whereas Yamin et al. [104] examine repair cost, downtime as well as functionality losses and Fu et al. [109] include casualties. Hassan et al. [1] compute the resilience of schools based on a framework consisting of two separate indices for quantity and quality. Generally, however, the mere quantification methodologies reveal significant similarities, and the essential difference is created

[4] https://gpss.worldbank.org/en/glosi/overview

by the used indicators and the quality of the underlying data [106,116]. Beyond the scope of ESR, alternative methodologies exist in various ways, many of which are similar in their overall approach to assessing the seismic fragility and vulnerability of general buildings [117]. Overall, the more conventional and 'simple' methodologies achieve good results. However, their application is limited by several factors. First, most methodologies are designed only for specific building types based on the mechanical properties of the different building construction types. In the context of school buildings, so-called RC (reinforced concrete) buildings [102,104,105,109,111,118] or (unreinforced) masonry buildings [106,107,111,119] are frequently targeted, as these are most common in the regions under consideration (mostly Asia). Additionally, modern wooden school buildings are considered by Miyamoto [115]. Due to the different mechanical properties of the building types, these results cannot be easily adapted for other applications. Another problem in this context is these building types' data dependency and availability. In many cases, no empirical data are available for the computation of fragility or vulnerability functions, so numerical techniques such as finite element, Monte Carlo simulation, or IDA must be applied to obtain reliable results. However, the application of these techniques takes time and requires appropriate knowledge. More progressive methodologies, such as neural networks, can eliminate the timely aspects, making the application much less time-consuming [105]. However, the complexity of the methodology is significantly higher, and it is more challenging to provide the necessary conditions. Other novel and promising approaches include Agent-based Modeling (ABM) and Digital Twins. However, these have yet to be applied to quantifying the seismic resilience of school buildings (Digital Twin) or the methodology (ABM) is primarily used to portray the system interdependencies of community structures. However, researchers recognize the problem that existing methodologies are rarely able to incorporate interdependencies between buildings and social structures. Instead, most consider school buildings in isolation without taking into account other community resilience aspects that have an impact on education system resilience. Thus, it is not sufficient to examine sole indicators such as repair time, downtime, or recovery time through mathematical models alone. Rather, it becomes necessary to include external parameters such as political strategies or decisions and other environmental influences [49] or to embody the methodologies in comprehensive tools for risk management or life-cycle frameworks [109]. Furthermore, a common limitation is a practical application since many of the proposed methodologies have only been tested in theory or applied in case studies to a limited extent. To improve the existing methodologies' reliability and detect errors, they have to be applied and improved with further data and scenarios in the future [97,104–106,109].

4.1.2. Thermal energy and air contamination

Regarding thermal energy, two contrasting approaches to educational building resilience are combined. On the one hand, Carofilis Gallo et al. [97], Grassie et al. [120], Heracleous et al. [121] and Stephen et al. [122] investigate the energy efficiency of school buildings and propose solutions on how to prevent hypothermia or save heating costs and cooling demand. On the other hand, Grassie et al. [120] and Gómez et al. [123] study the danger of heat waves, which are rapidly gaining relevance due to climate change [19], and develop options to prevent classrooms from overheating in the summer. Grassie et al. [120], Gómez et al. [123], Heracleous et al. [121] and Stephen et al. [122] use specialized dynamic energy simulation software and compute relevant underlying data with mathematical models. Due to the limited research in this area (at least within the eligibility criteria), a comparison is difficult. Essentially, the methodologies are suitable for identifying measures that can be implemented to counteract the overheating of classrooms through the retrofit of buildings. For example, facade planting [123] or shading and ventilation [122] are possible means to achieve positive results. However, some disadvantages of the methodologies are mentioned. For example, they cannot measure individual variables separately but exhibit large statistical errors [120]. Thus, the exact determination of indoor temperature and the influence of ventilation could be determined inaccurately [120]. Therefore, researchers recognize the need to advance these methodologies by increasing available data through future iterations on additional factors (e.g., terrain) or the inclusion of school building professionals to determine appropriate performance settings [120]. Additionally, the assessment of the cooling load required to achieve students' comfort under current and future climate projections could be included as well as assessments of achievable energy savings [122]. Considering the general resilience of buildings to heat waves, it is evident that more advanced quantification methodologies already exist [124]. However, these still need to be adapted to the conditions of school buildings. Consequently, research in this area needs to be significantly expanded to strengthen ESR against heat waves in the future. Regarding energy efficiency, the concept of virtual reality to pursue a holistic simulation approach to retrofitting school buildings is applied by Heracleous et al. [121]. Overall, research on quantification methodologies seems to be more advanced in this research area, as there are other approaches besides simulations via virtual reality as well, such as artificial neural networks or Bayesian inference [125]. Nevertheless, limitations and potential for improvement still exist. On the one hand, the methodologies are related to individual buildings and must be escalated to higher (national, global) levels to make them applicable on a large scale [120]. Among other things, this requires adaptation to different environmental and social conditions, e.g., through the involvement of experts [121]. On the other hand, fully integrated solutions (multi-hazard) could be elaborated [97]. Besides, measures to both increase energy efficiency and heat wave mitigation impact air quality [126]. In contrast to the dimensions of resilience mentioned so far, the number of studies on air contamination in school buildings is significantly lower. One study was identified that addresses energy retrofit and air contamination independently [120] using dynamic building simulation software based on different mathematical models for data input. So far, only a few contaminants have been investigated for application in school buildings, which do not significantly impact education continuity (CO_2, NO_2, and particulate matter). Nevertheless, the data availability can be further expanded on critical elements of the system (e.g., the granularity of weather or NO_2 concentration) [123]. Furthermore, the SARS-CoV-2 pandemic has demonstrated that pathogens can be air contaminants relevant for education continuity. Accordingly, the research area on air contaminants is important for ESR and must be considered mandatory in a comprehensive approach.

4.1.3. Floods

A single publication was identified that addresses the resilience quantification of educational buildings against floods exclusively [55]. Although it cannot be considered a comprehensive approach, it uses the same linear quantification methodology originating from the Climate Disaster Resilience Index (CDRI)(see Section 4.2), resulting in a less detailed and less complex methodology but in a wider scope than most low-dimensional approaches. Although floods occur frequently and some literature exists on the impact on education continuity [127–129] there is a lack of ESR quantification methodologies dealing with floods exclusively. However, other studies [57] were identified that include floods but adopt an integrated and multi-hazard approach. These are discussed in detail in Section 4.2. Nonetheless, regarding the part of the methodology dealing with floods, research gaps such as the impact of lateral flood loading on masonry walls can be identified [57]. Beyond the scope of ESR, other approaches that use much more complex and detailed methodologies can be found in the broader literature on resilience to floods [130]. As an example Pohl [131] and Sen et al. [59], who use probabilistic models, can be mentioned on the one hand as well as Sen et al. [132], who extend the probabilistic models (in this case Bayesian networks) by applying GIS tools on the other hand. Moreover, several other studies apply simulations [133], a combination of further mathematical models [134] some of which are based on underlying indices [135] or more progressive approaches such as fuzzy models [136] allowing for a much more detailed consideration. Overall, research on flood hazards appears to be very advanced, and the types of methodologies share strong similarities with those from the seismic resilience category. Although they are not specifically related to the education sector, similar structures (e.g., residences or Critical Infrastructures) are being examined, suggesting that a successful transfer of methodologies to educational facilities is likely possible by applying a reasonable adaptation effort.

4.1.4. Wind storms

Additional addressed scenarios concerning school buildings include hazards from wind storms such as tornadoes or typhoons/hurricanes. Several studies addressing these issues have been identified that share similar approaches, using different mathematical models based on empirical data [116] or applying Monte Carlo simulations to generate the necessary data [29,119]. Retrofit options [116,119] are examined, as well as post-disaster reconstruction [29]. Due to the slightly varying approaches and underlying metrics, different advantages of the methodologies can be mentioned: Acosta et al. [116] use variables to allow measurement of economic alongside structural damage, while Masoomi and van de Lindt [29] propose a versatile methodology that can examine virtually any possible tornado scenario and integrate dependencies arising from school building networks. Wang et al. [119] additionally elaborate new archetype school buildings, thus providing the basis for more extensive analyses. However, these newly developed archetypes only apply to reinforced masonry school buildings, and additional archetypes must be developed for further improvement [119]. Moreover, the methodologies' level or accuracy of disaggregation could be improved as the proposed approaches examine entire buildings as one unit and cannot distinguish individual components. This is important because the considered school buildings are used as emergency shelters. Thus, some components, such as the roof, have a higher significance than others, and the possibility of analyzing them individually would be advantageous [116]. Although a versatile methodology exists, it cannot be easily generalized as no two disasters are the same [29]. To remedy this deficit, empirical restoration data of communities recently impacted by tornadoes could prove beneficial for improvement in precision and accuracy [29,116]. Beyond that, using Agent-based Modeling, Aghababaei and Koliou [60] propose a resilience metric for education system resilience against tornadoes. Since this approach is designed to examine a school's entire community comprehensively and takes into account many other criteria in addition to the structural characteristics of the school buildings (e.g., interdependencies to Critical Infrastructure such as electrical power or water supply networks, and the availability of shelter options for students), the scope is much broader than with the other methodologies. This results in the ability to adapt the agents' behavior to implement different strategies and compare the quantified results to improve the stakeholders' decision-making, which can be seen as the main advantage. However, as many possibilities are imaginable, the methodology needs further application using different parameters (e.g., to identify methods to build redundancies of power supplies or other Critical Infrastructures). Similarly to the other low-dimensional scenario types, a wider range of existing methodologies is available beyond the application to the education sector. Wang et al. [137] propose another form of disaggregation by phrasing an inverse multi-objective optimization problem. In addition, artificial intelligence (neural networks) has been employed to measure building resilience towards wind storms as well [138,139]. Furthermore, the link between the structural resilience of buildings and reduced community resilience resulting from the collapse of an existing building is frequently addressed [140].

4.2. Multi-dimensional approaches to ESR quantification

When considering disaster resilience, it is crucial to not only analyze individual disasters in isolation but also to recognize the significance of interdependencies and the occurrence of multiple simultaneous catastrophes [141]. Two distinct approaches can be discerned: multi-hazard approaches and comprehensive approaches.

4.2.1. Multi-hazard approaches

Several publications exist that introduce resilience quantification methodologies to multiple hazards. These multi-dimensional approaches use comparable methodologies to the low-dimensional approaches. Their strength resides in either the underlying indicators and variables being chosen more generally and therefore applying to different hazards in an integrative way [49], or considering individual hazards but combining them through different mathematical models to examine a larger context subsequently [118]. Furthermore, Dhulipala et al. [142] raise a methodology that addresses temporal interactions between multiple hazards [142]. These properties result in an ability to perform more detailed analyses [118] as well as to capture, quantify, and integrate interdependencies in systems of systems [142]. The multi-dimensional studies focus not only on a wider range of hazards but also on the interconnectivity and interdependencies of school systems [57,60] as well as interdependencies to other critical infrastructures (e.g., health care) [75] and access to school buildings or the social vulnerability of school communities [57]. These linkages are examined in various ways, and the overall proportion of socio-immaterial components is higher than with the low-dimensional approaches. However, this more extensive consideration also inevitably leads to an immense computational effort when the level of detail is increased [142]. To overcome these problems, more progressive methodologies like physics-informed neural networks are recommended to reduce the computational burden [142]. Beyond that, introducing and applying a unified taxonomy and developing a comprehensive dataset of various school typologies is recommended to strengthen collaboration between stakeholders and improve prioritization and resource allocation when considering multi-risk scenarios [49].

4.2.2. Comprehensive approaches

Several studies [5,6,56,143] exist that are based on varying qualitative indices and pursue an as comprehensive as possible approach. Most of these studies utilize the same quantification methodology originating from the Climate Disaster Resilience Index (cf. [144,145]), which was originally developed to measure urban climate disaster resilience of Asian cities. The latter possess the lowest complexity of all considered methodologies because they use linear mathematical models exclusively. Its basis is identical in all cases and achieves quantification of ESR through expert judgment. Means of standardized questionnaires and 5-point Likert scales implement data collection, but differences can be found in the weighting of the indicator values. Shiwaku et al. [143] use a scale of 1 to 3, while Tong et al. [56] use a scale of 1 to 5, and Parajuli et al. [6] base the weighting on the assessor's position or role. Mirzaei et al. [5] do not apply any weighting of indicator values. The simple design of data collection can be complemented by technical instruments (mobile application tools) to increase efficiency [6,49]. However, the data collection can be impeded by participants' unawareness or limited knowledge about the required data [5,6]. Nevertheless, the surrounding school community can be better involved in the process as they are part of the data collection, and direct feedback can be given [6]. In addition, the methodology can be used in iterative circular processes such as the PDCA cycle, providing a long-term mechanism for measuring school resilience [143]. However, the methodology is not an absolute but a relative measure particular to one school set in a specific environment [56] and can only be used for schools with similar structures without adaptation [5,6]. Apart from this, the methodology's current inability to measure education sector governance is a major downside that calls for further development and research [143].

4.3. Integrated consideration and interpretation

Following the findings of Lu et al. [146] in the context of urban resilience, there seem to be two basic methodological levels for quantifying ESR: the structural–physical and socio–immaterial levels. While most eligible studies focus mainly on school premises and examine the structural–physical resilience of school buildings, very few consider social or immaterial values. Furthermore, economic considerations are mainly linked to the rebuilding or retrofitting of buildings. However, the education system comprises far more components (see Fig. 4) that a comprehensive approach to ESR quantification should encompass [21,147]. Given potential disruptions such as disasters and similar events (input) are then influenced by all of these components (gray box), resulting in observable effects (output), e.g., a state of education continuity or disruption.

education system of systems

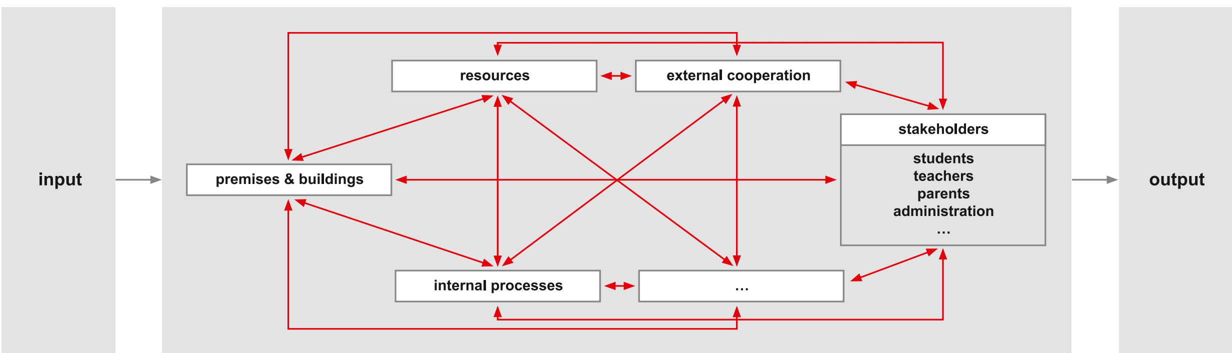

Fig. 4. Gray-box with components influencing an education system of systems based on the systems theory according to Chorley and Kennedy [148], own presentation.

Furthermore, it can be recognized that careful consideration of ESR quantification should not be limited to the education system itself, but that it constitutes a subsystem of other complex systems and must be addressed in conjunction with its environment [75]. These complex systems can adapt to external conditions and through their inherent interdependencies continuously influence each other [149]. For example, school buildings exhibit massive dependencies on Critical Infrastructure [29]. Vice versa, the education system can have a positive impact on other systems and increase their resilience through contributions to civil protection such as

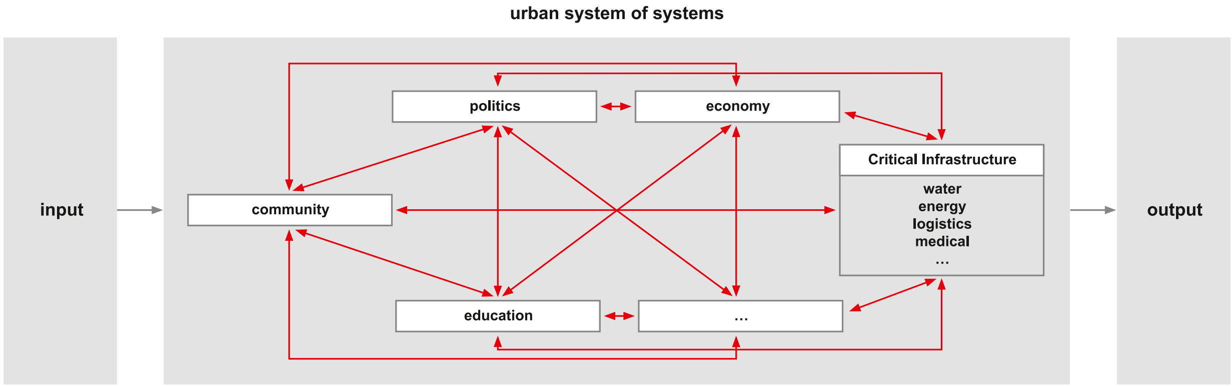

Fig. 5. Gray-box with components influencing an urban system of systems based on the systems theory according to Chorley and Kennedy [148], own presentation.

the use as emergency shelter [7] or in crisis preparation through disaster education [8,150] as presented in Fig. 5. Especially in this area, there is a particularly strong link to community or societal resilience [151].

To account for this high level of complexity, increasingly comprehensive methodologies that capture multidimensional factors such as interdependencies and cascading effects are being developed [152]. This is important because urban systems and communities are growing steadily and are increasingly interconnected with the consequence that urban planning can no longer be accomplished in isolation but rather should be pursued at a fully integrated level (including urban planning, school planning, civil protection planning, and others) [29,109,153,154].

4.3.1. Classification of the reviewed methodologies for ESR quantification

Presupposing an underlying education system of systems for quantifying ESR, none of the methodologies examined in the scoping review can be characterized as exhaustive and fully comprehensive. Instead, the analyzed methodologies vary significantly in three variables: the level of detail, complexity, and the considered scope. The level of detail describes how precisely something is examined. It can range from rather general assessments that give a rough overview to very detailed evaluations that examine individual characteristics with great care. As a consequence, the level of detail has a direct influence on the other two variables: Usually, the higher the level of detail, the higher the complexity of the methodology, so that a large variety of adjustments can be made to account for subtle differences in the assessment. At the same time, the development and application of a more complex methodology are usually more time-consuming, resulting in a reduction of the studies' scope. This is evident, for example, given that there are a few approaches that aim for a more comprehensive scope and rely mostly on very simple linear mathematical models for quantification, while most studies possess a high level of detail and use more complex methodologies but focus on individual components of ESR or isolated disasters. Fig. 6 illustrates these relationships by plotting the examined studies merged into clusters according to their characteristics regarding the three variables. The darker a data point appears, the lower its value on the z-axis (level of detail), and accordingly, the more transparent a data point is, the higher its value on the z-axis. Since this scoping review provides a general overview rather than a systematic investigation of the individual methodologies, no quantitative engineering methodology was applied to assign the individual values to the reviewed quantification methodologies. Instead, a subjective semi-quantitative assessment was employed to classify the reviewed quantification methodologies based on the information in the literature that has been presented in this study. Therefore, an ordinal – rather than a metric – scale is used (low to high) to represent the different characteristics of the quantification methodologies. Fig. 6 provides a visual representation of the classification and helps to estimate the inherent characteristics as well as the relative ranking of individual methodologies along the three dimensions in comparison to others, thereby highlighting their differences. While acknowledging the inherent subjectivity involved, the 3D scatterplot serves as an outline supported by evidence from the reviewed literature, as well as a basis for discussion and future more detailed, systematic investigations. The figure was generated using python 3.10 [155] and matplotlib [156] version 3.6.2 [157]. To generate an interactive 3D scatterplot, the applied Python code is provided with the supplementary material. Although a rather coarse, semi-quantitative classification was chosen, exact quantitative values for the individual coordinates of the methodology clusters had to be specified to generate the figure using matplotlib (see lines 5–13 of the Python code). For this purpose, the axes were assigned the values 1 (low) to 3 (high) and a step size of 0.5 was set. Subsequently, the values of the individual methodology clusters were assigned as precisely as possible in accordance with the initial semi-quantitative estimate classification derived from the reviewed literature.

The graph indicates that no methodology has achieved a high score in all three dimensions and could thus be classified as fully exhaustive. Instead, the methodologies are either very specialized and low-dimensional (low scope) but have a high level of detail, which entails a certain complexity, or they try to achieve a high scope and as a consequence are less complex as well as less detailed. The latter represent more of a 'Pareto approach' because they cover a large range of indicators and dimensions of ESR through relatively low effort, while the low-dimensional approaches provide a very detailed impression of a narrow range.

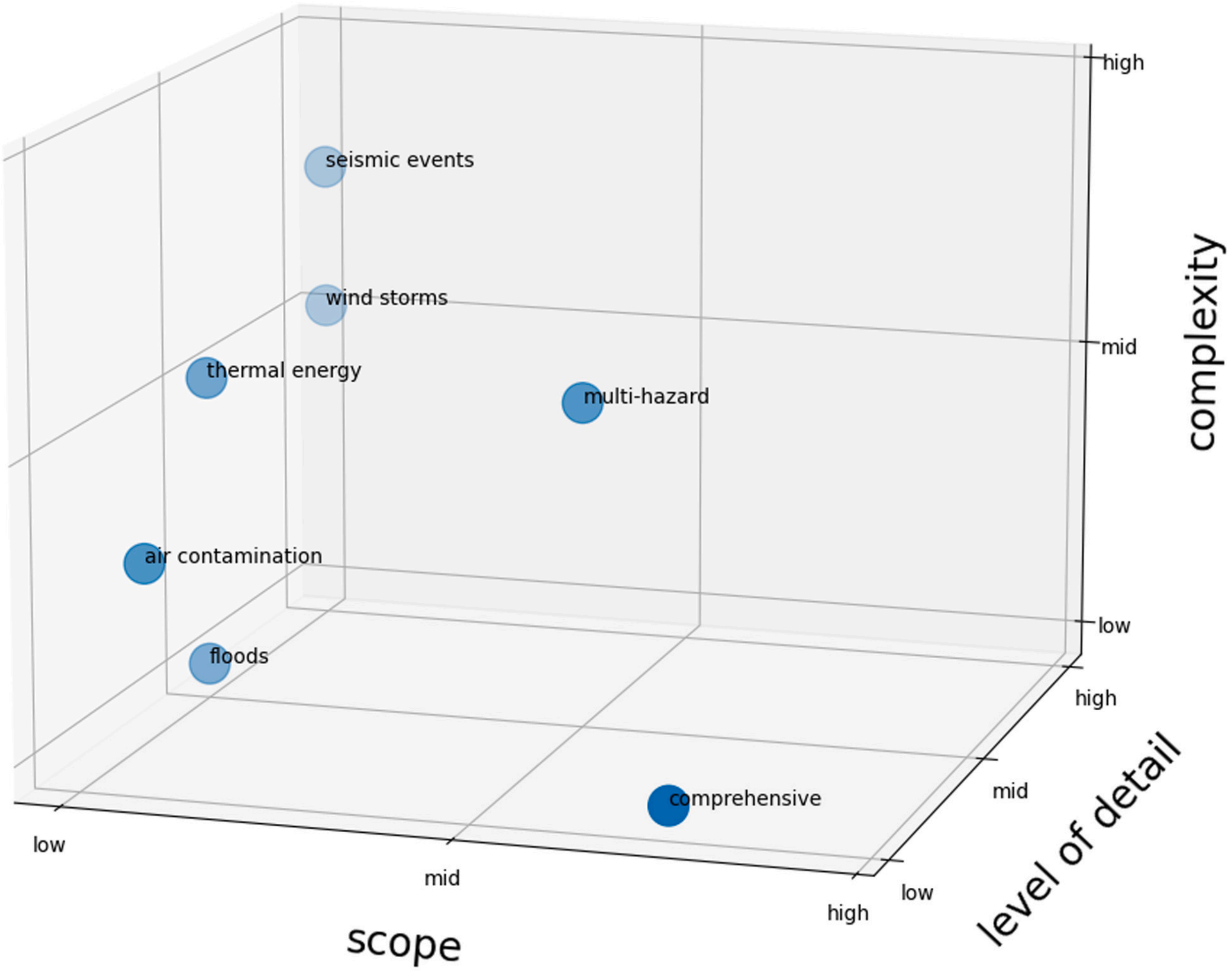

Fig. 6. Classification of identified quantification methodologies across the three dimensions: scope, level of detail, and complexity clustered by disaster types and approaches.

4.3.2. Derivation of a methodological framework for ESR quantification

Several considerations can be derived from these findings: The various approaches have different advantages that complement each other well. Therefore, it might seem desirable to combine them in a particular way. This combination could be achieved by merging them into an exhaustive methodology that performs well across all three dimensions. The procedure would, however, raise many questions. For example: How can the individual results of the methodologies then be integrated or interconnected at a systemic or qualitative level? Or how does normalization of the different results occur on a mathematical/quantitative level? Current research indicates that index-based approaches are promising, and an increasing number of studies attempting to develop indices are being conducted. Both for full-scale considerations (cf. [86]) and for examinations with a high level of detail (cf. [158]). However, similar to the research field of urban resilience, the identification of appropriate indicators is a constant issue of discussion because of the different research domains considered and integrated [152]. This emphasizes the importance of a combined resilience taxonomy, as the choice of the level of analysis and the limitations of the underlying theoretical models are key factors regarding its measurement [159]. Nevertheless, extensive quantitative methodologies to connect different dimensions are currently unavailable.

Furthermore, the issue is raised whether a 'Pareto approach' is sufficient for a first approximation and that more profound methodologies are merely used as an addition if the demand is recognized or the necessary expertise and/or the necessary means are available. Especially against strained public budgets, prioritizing essential deficiencies and remedies can be favored rather than aiming for full-scale improvement. Moreover, the indices and methodologies must be adapted to social, geographic, and other circumstances and conditions [21]. In Germany, for instance, it may be less relevant whether a building is earthquake-resistant than in other regions, such as Asia. Additionally, building codes and earthquake zones already provide structural standards that increase the seismic resilience of buildings [160]. Besides, the review shows that many methodologies apply only to limited areas or conditions, as they examine very specific characteristics (e.g., certain construction types of school buildings in well-defined geographical regions). The high diversity of overall school communities' cultures and other environmental influences can be anticipated by considering the worldmap depicting the case studies' locations provided with the supplementary material. The identified studies cannot be narrowed down to specific cultural or geographic locations but originate from large parts of the world. Consequently, the adaptation of the methodology to a specific region is increasingly essential. Therefore, it may be preferable to develop a basic framework that can be adapted to the circumstances of the school community under consideration, with only the essential aspects being investigated at a higher level of detail rather than a general, all-encompassing methodology.

This strategy also appears promising from a practical point of view, as the methodologies are likely to be used by practitioners who are not experts in quantifying resilience, such as teachers, principals, parents, public bodies, or politicians. This is relevant because, although the application of some of the more detailed and specialized methodologies is presented as 'simple' in comparison to others, nevertheless a previous thorough education is necessary for their application, for example, in the field of civil engineering [49,103]. However, the involvement of practitioners and stakeholders in participatory approaches is essential for adapting the methodology to the given circumstances [5,6]. As shown in Fig. 7, it seems more promising to design a survey within this group of stakeholders in a methodologically simple fashion and to prioritize demands for action through Likert scales or similar (Top-Down). Once the most significant weak points have been identified this way, more in-depth analyses can be conducted by relevant experts in the respective fields, if necessary (Bottom-Up).

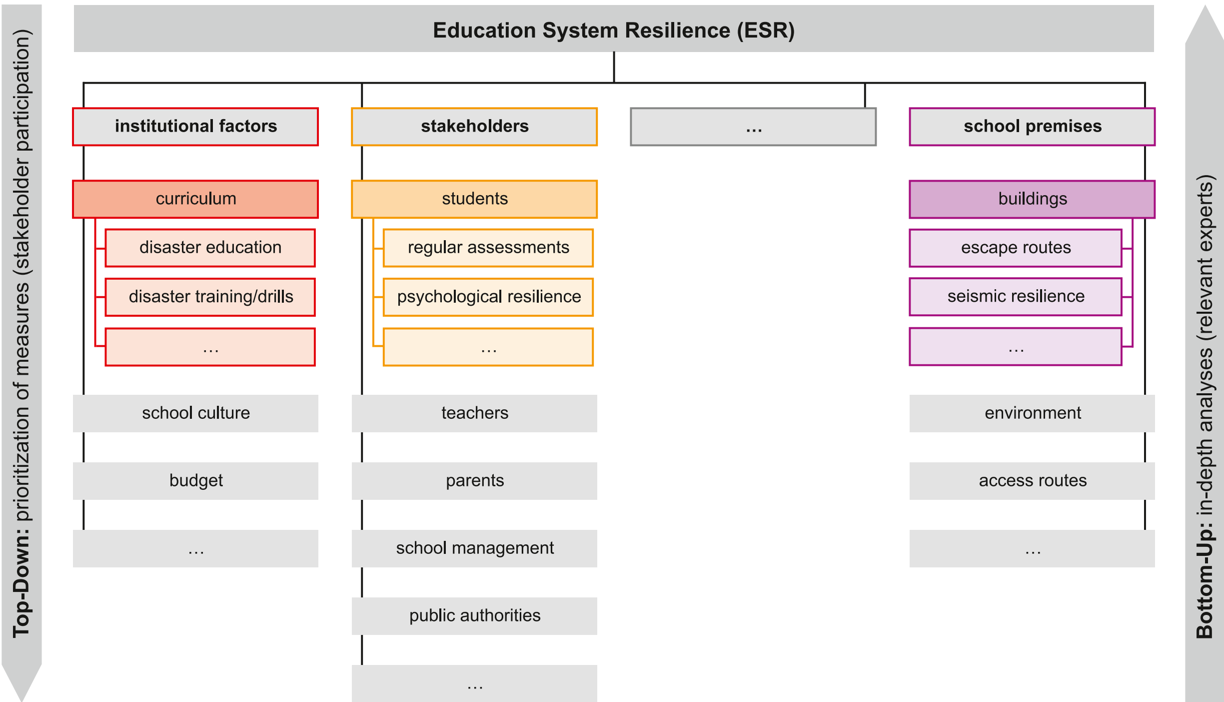

Fig. 7. Schematic of a proposed methodology for ESR quantification including opposing approaches depending on the respective stakeholders.

Designing the proposed quantification methodology for ESR as a framework that can be adapted to individual school communities' circumstances enhances its relevance and applicability. It allows for a more nuanced understanding of the education system's specific strengths and vulnerabilities [6], leading to targeted interventions. However, education systems vary widely across different regions and countries and resilience assessments need to account for the diverse contexts in which educational institutions operate. Therefore, developing an assessment framework that is flexible enough to accommodate these variations while robust enough to maintain its inherent rigor throughout the adaptation process and provide continuously valid results is very complex. By adapting the proposed methodology to different regions on a global scale, direct comparability of results cannot be ensured as different factors and characteristics are applied. This is equally true for regional assessments when conducted in a periodic application of the methodology over time in the context of life cycle frameworks as proposed by Shiwaku et al. [143]. Due to changes in the school community (such as demographic developments) or altered external influences (such as climate), the conditions shift and the methodology may need to be re-calibrated. In both cases, the resilience scores are not easily comparable, which complicates the analysis of the methodology's benefits as well as the implemented measures. Especially regarding future resilience assessments, climate change adaptation and the prevention of education disruption due to unacceptable thermal conditions within educational buildings will become increasingly important regardless of the educational institutions' location [19,120,123,161]. Similarly, pandemic threats and corresponding resilience metrics must be considered in the future as well [162,163]. As a consequence of this ever-changing circumstances, it can be considered irrefutable that the underlying framework is placed under constant adaptation pressure, thus significantly complicating the long-term comparability of resilience scores. However, when taking a larger perspective, the process of adaptation may facilitate knowledge transfer and exchange between different regions and education systems. Lessons learned from successful adaptations could inform best practices in other contexts.

Furthermore Cai et al. [164] state that local authorities are essential in helping a school community adapt to their specific circumstances and thus strengthen their resilience. By including local governments and community leaders in the methodological process of prioritizing measures to enhance resilience, they are involved in the whole process from start to finish and can initiate the required steps in a short manner of time. Thus, involving regional governments and local leaders can ensure that the necessary resources are made available to implement the identified measures. Since political debates and decisions as well as administrative procedures can constitute tedious processes, early involvement of the relevant bodies is an important step in allowing measures tailored to the specific circumstances of educational facilities to be implemented quickly and efficiently as is generally advised within the Sendai Framework for DRR [50]. Beyond that, stakeholder engagement can have a very positive impact on the implementation and future design of the identified measures since each stakeholder has his or her own perception of the issues at hand, based on his or her own values, concerns, and objectives [165]. Langrafe et al. [166] demonstrate that sharing information, mutual trust, involving stakeholders in decision-making procedures, and taking their interests into account adds significant value to the process and equalizes the inherent risks. Therefore, this collective involvement is likely to gain more support and acceptance for the proposed methodology as well as to foster a shared and stronger responsibility for resilience-building efforts. However, the process of data collection may encounter hindrances stemming from stakeholders' lack of awareness or limited knowledge regarding the considered issue [5,6]. In general, local data availability and quality may vary (as addressed by many eligible studies of the scoping review), impacting the accuracy and validity of the resilience assessments. For one, the lack of generalizability of results due to the uniqueness of disasters poses a significant challenge [29]. To address this, some methodologies suggest an increased use of empirical data from disaster-impacted communities to enhance the resilience quantification process [29,109]. However, gathering reliable data can be time-consuming and resource-intensive [167]. Therefore, many methodologies suffer from a small number of empirical observations, often limited to single case studies posing a challenge for accurate analyses [57,97,105,111]. To overcome this, it is essential to increase the data availability by conducting further case studies. Moreover, the disaggregation of data is not always precise enough, leading to the inclusion of factors that may distort the results [57,116]. This can be remedied by acquiring more damage loss data as well as refining the used methodologies or acquiring complete geo-referencing and expanding data resolution (for example through the more in-depth application of GIS tools), thereby increasing precision and accuracy of the resilience quantification [57,116,120]. Furthermore, some methodologies have a limited scope as they only apply to specific building types [97,104–106,109,118,120]. Extending the methodologies to other types of buildings and architectural structures can improve its robustness, applicability, and versatility [97,104–106,116,119]. Beyond that, the development of a comprehensive data set of typical, defined structural school typologies can further aid this process [49]. Additionally, resilience assessment data may involve subjective elements, such as disaster knowledge [56], disaster affectedness [55], or personal and social competence [7,74]. Incorporating qualitative data, stakeholder perspectives, and subjective indicators can add further complexity and require careful interpretation and validation.

Overall, the more in-depth methodologies still seem to have potential for development, and it depends very much on local factors (such as data availability, type of existing school buildings, frequency of disaster occurrence or support from local stakeholders, and thus the ability to conduct empirical studies, etc.) how well the bottom-up approach of the proposed framework can be implemented at this time. To address all these diverse constraints and challenges, a lot of research still remains to be undertaken and it requires intensive interdisciplinary collaboration.

4.4. Limitations

There are some limitations to the scoping review. These will be addressed to improve the future elaboration of ESR quantification methodologies through scientific research [168]. There is evidence that the quality of abstracts in software engineering can be poor and that it is only sometimes possible to assess the relevance of an article by consulting the abstract alone [169]. Therefore, as the research area of ESR quantification is still in its nascent phase and there have yet to be any investigations conducted on these aspects, it must be assumed that relevant studies have been incorrectly excluded. It is striking that the included publications only comprise peer-reviewed journal articles and conference papers. Although gray literature was explicitly included, no such publication could be identified. This might be caused by the fact that no database was chosen specifically for gray literature. Identifying such databases or using more general search systems could improve the detection of gray publications. A similar situation applies to publications in German. Moreover, what is equally prominent is that only one study [170] has been identified that addresses the impact of COVID-19 on education (or classroom hygiene in general). However, it was not considered eligible as it poses no quantification methodology but a decision-making aid. More detailed attention to this point may be needed in subsequent work, for example, by adjusting the search strategy. Furthermore, no study that addresses violence against children, such as abductions, sexual violence, or shootings, could be identified. What is striking in this context is that no case study was considered eligible, focusing on the continent of Africa. Yet, this type of threat can be observed frequently within this continent [171]. Therefore, it must be taken into careful consideration that the selection of search terms may not have adequately represented these types of threats and geographic locations and that future research must adapt and refine these. Especially considering that at least one study does exist that measures the vulnerability of schools to floods in Kenya (cf. [172]). However, as the vulnerability perspective was not pursued or adopted, this study did not meet the eligibility criteria either. This circumstance leads to another crucial aspect that has to be considered: an essential weakness of the scoping review is that the perspective of vulnerability was not included. The existence and availability of several publications addressing this perspective show that this term is essential, and the related publications would complement the quantification outline. Especially when considering the terms risk, hazard, exposure, and vulnerability, the latter overlaps to the greatest extent with resilience-building approaches [173]. Therefore, identifying relevant publications on ESR quantification needs to be extended to include terms such as vulnerability and possibly others in the future to generate a more holistic picture. Additionally, since the eligibility criteria excluded the psychological resilience of the involved stakeholders, publications on quantification methodologies for the psychological resilience of students, teachers, parents, and other stakeholders cannot be assessed at this stage. However, preliminary literature searches indicate that considerable research is available in this area (cf. [174]) that should be included in future elaborations. Lastly, conducting an independent review on the quantification methodologies for ESR to earthquakes is worthwhile, as the literature on school buildings' resilience quantification to seismic events is sufficient and well-developed. Here, a more in-depth review would be useful. Nevertheless, it is evident from the scoping review that the key results and conclusions will remain mostly unaltered by considering additional publications.

5. Conclusions

Some key insights into education system resilience quantification methodologies could be obtained. Considering seismic resilience to school buildings, many well-researched and internationally recognized quantification methodologies exist that achieve good results using mathematical models and can be handled and applied by most engineering graduates. However, a few methodologies pursue more complex approaches, such as Dynamic Building Simulation software, GIS tools, or neural networks. Several studies use differing underlying indicators to achieve a high level of detail. The main limitation is the availability and quality of data as well as the limited applicability due to the underlying building characteristics. Expanding the methodologies to different structural typologies and integrating real statistical data could improve the methodologies' accuracy in future applications. Current research focuses on the different levels of detail and the indices and frameworks used to quantify seismic resilience. However, these subtle differences and the resulting advantages and disadvantages are irrelevant to the fundamental consideration pursued in this scoping review. It is obvious that a robust body for assessing seismic resilience exists and that it can be quantified effectively in general. Nevertheless, there is a need for further research, especially to adapt the techniques to individual local conditions or to expand the methodologies to other building types and improve data quality and availability. For the field of thermal energy, only a few studies exist that portray promising methodologies to improve energy efficiency and heat wave mitigation of school buildings (mostly using specialized Dynamic Energy Simulation software) and adapt the buildings' performance to the students' requirements under a changing climate. However, the methodologies could be more detailed as they cannot measure individual variables separately and pose yet to resolve statistical errors. Increasing available data through future iterations on additional factors and including school-building professionals to improve existing methodologies is desirable. Especially regarding air contamination and floods (in the context of ESR), the available studies must be more extensive to provide a relevant statement. Both eligible studies quantify ESR, but methodologies beyond these must be developed. To improve the quantification of flood resilience, researchers can draw on existing methodologies beyond the scope of ESR, such as Bayesian networks, GIS tools, simulations, or fuzzy models, and adapt them to educational buildings. Research on air contamination seems to be not very advanced in general, and extensive research gaps are portrayed, such as extending the investigation on more contaminants and the expansion on critical elements of the system. Little studies likewise address the quantification of education buildings' resilience to wind storms. While versatile methodologies exist, the methodologies vary slightly due to the differing underlying indicators, and several mathematical models are used to quantify resilience. However, these are often only applicable to specific school building types, and additional models must be developed for further improvement. Moreover, the disaggregation of these building types could be improved as different parts (e.g., the roof) impact building resilience more than others. An isolated examination of these parts would be advantageous. Additionally, gathering empirical restoration data of recent tornadoes could prove beneficial for further development in precision and accuracy. A growing number of approaches exist within this research area that addresses interdependencies between several schools or even within a larger school community, for example, using Agent-based Modeling. With this approach, it is possible to simulate and compare various strategies, including different parameters, to improve decision-making.

When considering multi-dimensional approaches, two different strategies can be distinguished. Multi-hazard approaches apply similar or comparable mathematical models to low-dimensional approaches while adapting the indicators to multiple hazards or combining different mathematical models to reflect interdependencies and cascading effects. In contrast, more comprehensively oriented approaches based on qualitative indices provide a score for school resilience through simple-to-implement linear quantification methodologies. While multi-hazard assessments can capture a higher level of detail and maintain the integration of interrelationships, the computation effort and need for data acquisition can be immense. As a solution, the use of more progressive methodologies like physics-informed neural networks or the development of a comprehensive data set consisting of various school typologies and the introduction and application of a unified taxonomy is presented. However, this raises the demand for necessary performance skills and requires much research. Considering the comprehensive approaches, the methodologies are easy to use. Technical instruments can complement them to include various stakeholders and their operational, contextual, and empirical knowledge almost effortlessly. The main downside of this approach is the rather rough quantification posing more of a "Pareto-approach" than an in-depth measure. The key research gap involves increasing the level of detail while maintaining the methodology's simplicity and broad scope.

Beyond the scenario clusters, an overall perspective can be portrayed. On the one hand, the identified methodologies differ significantly in scope, level of detail, and complexity. On the other hand, no methodology can be described as fully efficient in all three dimensions. Two main approaches could be distinguished: the low-dimensional approaches, which investigate a very restricted subject with a high level of detail and rather complex methodologies, and more comprehensive approaches, which do not have a high level of detail or a high complexity but a wider scope. Overall, the progress in different research areas varies widely and all research areas are significantly more advanced in a broader context that does not focus on ESR. Therefore, more progressive methodologies such as AI or Digital Twins can increasingly be used to quantify education system resilience. All methodologies remain subject to further development and must be improved to address all facets of ESR. In this context, the inherent link to CSR could be explored in more depth to transfer knowledge of quantification methodologies to ESR. The key challenge arising from the findings of the review is understood to be the development of a methodology that uses both very simple and accessible techniques in the first step to engage all stakeholders in participatory approaches to prioritize essential deficiencies and weaknesses based on underlying social, geographic, and further conditions of the education system under consideration. In the second step, these deficiencies and weaknesses must be addressed using expert knowledge and more complex but detailed methodologies to develop individual solutions to quantify ESR. Additionally, this methodology must account for inherent connections to other complex adaptive systems (such as urban systems or community and societal structures), which may include interdependencies, cascading effects, or other multidimensional factors. Much preliminary work is still necessary to develop such a methodology. Especially the adaptation to regional conditions is an important challenge yet to be resolved.

Developing an integrated methodology, which can be adapted to the various circumstances of the school (environment) under consideration by its inherent structure and procedure, would be a powerful tool in ESR quantification. Following the Sendai Framework for DRR, the Sustainable Development Goals, and the Global Alliance for Disaster Risk Reduction & Resilience in the Education Sector 2023–2025 Strategy[5] this instrument could help strengthen equitable education by measuring the resilience of educational institutions and identifying the most pressing challenges and threats. Due to the impact of numerous factors, it is necessary to involve as many stakeholders as possible, on the one hand, during the development of the scientific foundation (links between ESR and community resilience, individual psychological resilience, civil protection, or urban systems can be identified), and, on the other hand, regarding the practical application of the methodology (students, teachers, parents, others involved in daily school life, school management, school administration, political bodies, and decision-makers). This article provides a (nowhere near comprehensive) attempt to aggregate the existing education system resilience quantification methodologies and derives a larger framework from them to achieve this goal.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijdrr.2023.103967.

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