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A taxonomy of pedestrian evacuation infrastructure for urban areas; an assessment of resilience towards natural hazards

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Abstract. Many people in the world live in hazardous environments and are susceptible to disasters. In the time of a destructive event, a resilient community must be prepared to mitigate the event and quickly respond. An effective mitigation plan can lead to fewer fatalities and damages. One of the most critical tasks for mitigation is the evacuation process. Wherein short notice time, overcrowding, bottlenecks in infrastructure and challenging terrain and topography may worsen the situation. Amongst other things, the evacuation process encompasses transportation infrastructures referred to as corridors, signs, pedestrian footpaths, and/or shelter infrastructures for keeping people safe. Evacuation infrastructure can also become damaged after the event; therefore, it's imperative to have a robust assessment of different evacuation infrastructures. This study will investigate the characteristics of the available evacuation infrastructure and outline the general drawbacks. A systematic methodology for reviewing articles has been implemented to understand how vulnerable cities can be more prepared, especially for pedestrian evacuation. An evacuation scoring system for pedestrians will be developed to investigate evacuation infrastructure in terms of different resilience features, such as redundancy, safe to fail, readiness, capacity. The most practical evacuation system will be estimated, with a final output being to provide the features of a successful pedestrian evacuation system for future policy use.

1. Introduction

Natural hazards are destructive events, however, their risk to individuals would be reduced by proper preparedness [2]. When it comes to natural hazards like tsunami, mass evacuation is inevitable. A prepared community has a clear evacuation plan. To ensure the highest survival rate during a tsunami, a city must have developed a proper evacuation infrastructure in advance, which aids the city's evacuation plan to achieve resiliency and step into a prevention stage [3].

The evacuation infrastructure contains different parts, including roads, sidewalks, evacuation zone signs, evacuation route signs, evacuation shelters, and supply chain during a disaster [4-9].

In recent decades, the notion that the resilience of infrastructures has become more critical to be analysed and quantified since the disruption impact them significantly influences humans [10, 11]. However, there is still an ongoing debate on how the resilience of infrastructures should be improved. Several researchers have provided solutions [10, 12] to enhance the resilience of infrastructures to withstand disruptive events.

A resilient evacuation plan would not be achieved unless all evacuation infrastructure components were resilient. Resilience in infrastructures can be described as the ability of individuals and communities to adapt to a disaster situation . This means resilience encompasses phases of; (1) adsorbing the shocks from the disaster, (2) efforts to adapt to the new situation, and finally (3) the capacity that a system is able to restore if the previous phase fails. Researchers have developed various tools to quantify and evaluate the system's resilience [13-16].

The main contribution of this study is as follows:

- To study records, which are identified based on search queries from various databases such as Web of Science, Science Direct, and Scopus, among others, focusing on resilience assessment of infrastructures;
- To understand what features and dimensions of resilience are essential for evacuation infrastructures
- To outline a strategy for considering the resiliency of pedestrian evacuation structures.

The rest of the paper is organised as, Section 2 includes the methodology of conducting this SLR. This section describes the research questions, records searching process, and eligibility criteria of inclusion and exclusion of records. The comparative analysis results of the included studies are elaborated in Section 3. Section 4 states the discussion of features, models and techniques for resilience assessment on evacuation infrastructure obtained from the included studies. Finally, the conclusion and future research are presented in Section 5.

2. Research Methodology

In order to identify the recent trends, developments, and challenges for resilience aspects in evacuation infrastructures, there is an essential need to undertake a systematic review. This research gap has motivated us to find a resilience assessment model based on the previous resilience assessment done by other researchers, including a) required components of resilience in assessment analysis; b) addressing multiple features in resilience assessment. In order to address the discussed challenges, this study focuses on pedestrian evacuation infrastructures.This section will demonstrate the required steps to conduct a systematic literature review. Although there are various methodologies to pursue a systematic literature review, this study was structured based on a combination of various studies [17-19]. The designed Systematic literature review (SLR) shown in Figure 1 contains five stages, three to choose relevant articles, encompassing identification, screening, eligibility assessment, and two steps to summarise and interpret the evidence.

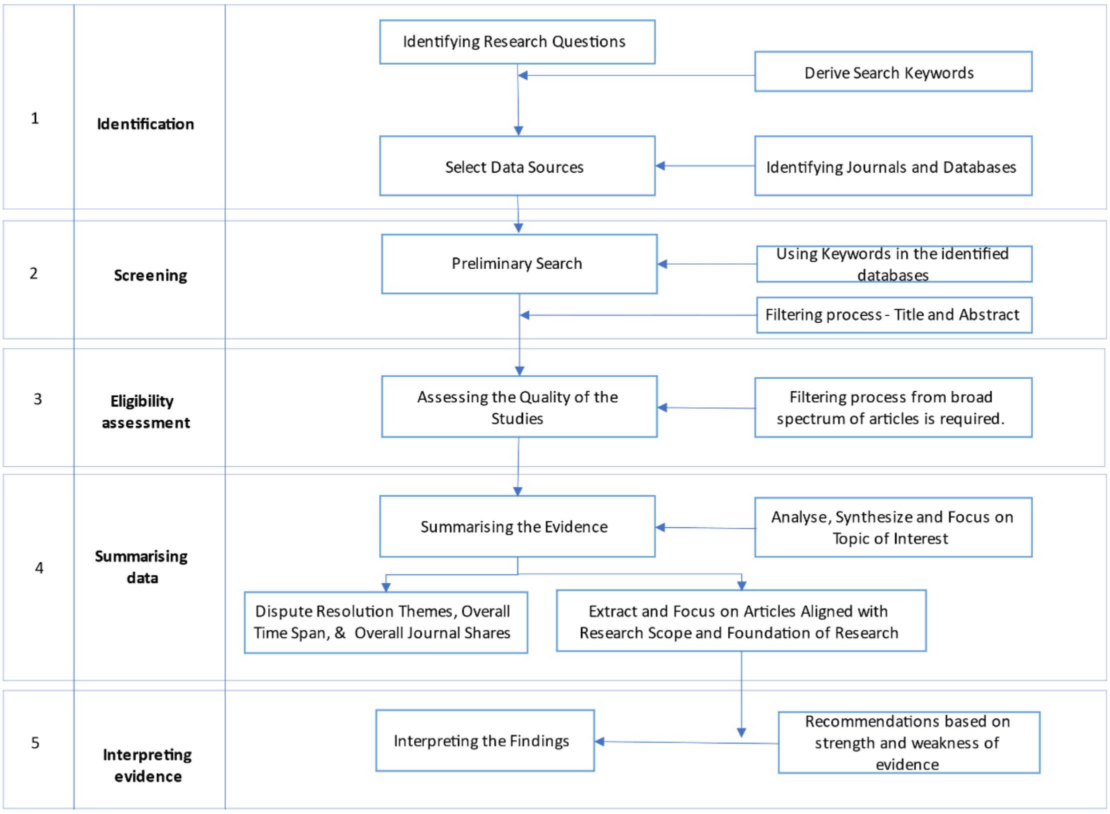

Figure 1. Research methodology graph

2.1.Identification of relevant articles

This study is performed to find a scoring system for pedestrian evacuation infrastructure in terms of different resilient features. Therefore, the research questions would be (1) What does a resilient infrastructure look? (2) What resilience features are investigated while evaluating evacuation infrastructures' resilience?

According to the research questions, the extracted key words were "pedestrian evacuation", "evacuation infrastructure", "resilience feature" and "resilien*". The (*) sign after "resilien" was used to identify and make sure any word containing these alphabets would not be missed out.

This study was conducted by using Web of science and Scopus search engines. The journals were selected within the domains of safety research, emergency management, natural hazards and engineering.

2.2.Screening

This section describes the screening methodology used in this study. The selected keywords were used in the identified search engines and a number of articles were selected for review. Furthermore, the main researcher initially screened all the documents for finding and deleting duplicates from different databases and evaluating the eligibility of identified records based on assessing titles and abstract.

2.3.Eligibility assessment

To ensure the selected article is in line with the research topic, the researchers of this study have identified four Exclusion Criteria (EC).

These exclusion criteria state the characteristics that are not considered in our research. Given below are the ECs for this SLR:

- EC1- studies that have not emphasised resilience assessments on infrastructures.
- EC2- studies that do not include at least two out of nine resilience features identified by [20];
- EC3 - studies that merely provide basic information about resilience assessment.
- EC4- studies that do not develop method/approach/model/tool Inclusion criteria are defined in such a way to conduct the SLR.

Also, to ensure the extracted data are reliable to conclude the desired outcome, a few Inclusion Criteria was checked as well. The (IC) for this SLR is stated as below:

- Must be published in a journal/ conference indexed in the databases as discussed in (section 2.1)
- Published within the last decade, January 2001 and November 2021
- Developed/Proposed a tool/method/Technique for risk assessment in infrastructures
- Must include one of the evacuation infrastructures mentioned in section 1.

The outcomes of the mentioned criteria are discussed in Section 3.

2.4.Summarising data

The Selected papers were studied carefully, and the findings of each article were highlighted. This study initially discusses generic research trends in the form of available mainstreams (themes) and overall time span; which is then followed by addressing the key research questions earlier outlined.

2.5.Interpreting the Findings

The data are synthesised and interpreted from the final identified articles. Recommendations are made based on evidence of strengths and weaknesses of the resilience assessment in each research study [21]. Accordingly, any weaknesses and shortcomings identified in the systematic review offer potential research avenues by addressing the research gap.

3. Results and Findings

3.1.Selected articles

The keyword search from the three search engines resulted in a high number of papers which by abstract screening and implementing eligibility criteria the shortlisted articles were cut down to 20 papers. Table 1 summarises the selection process.

Table 1: SLR article selection process

Search engine	Keyword	#Searched	#Screening	#EC&IC	Total
Scopus	Evacuation resilience	6382	35	14	20
	Evacuation infrastructure	2123	12	8	
	Evacuation infrastructure resilience	229	15	8	
Web of Science	Evacuation resilience	1839	51	15	20
	Evacuation infrastructure	855	78	15	
	Evacuation infrastructure resilience	99	78	15	

The shortlisted papers were studied carefully and a research theme has been outlined. Each research have been summarised according to the research themes classification. After synthesising the results, the knowledge gap has been identified. The following sections would provide a detailed explanation of each aspects in resilience assessment for evacuation infrastructure.

3.2.Research themes

Analysis of the literature found three major themes of scholarship when examining the resilience level of evacuation infrastructures from disasters. These three themes were: Features of resilience and resilience dimensions. All the themes have been clustered in different dimensions. Figure 2 shows the dimensions contributing to the resilience assessment of evacuation infrastructures.

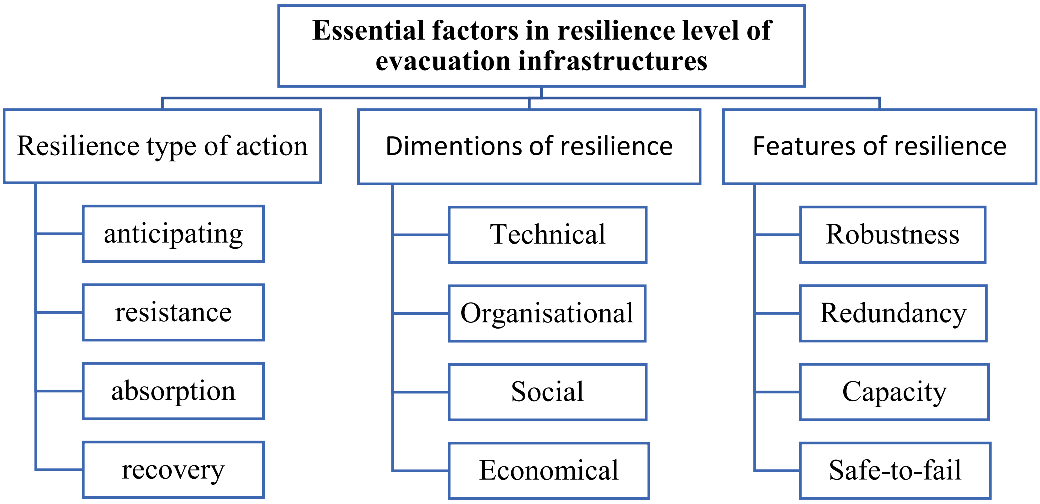

Figure 2: Research themes: Essential factors in resilience level of evacuation infrastructure

3.3.Resilience components and types of action

According to the definition of resilience, resilience activities start from before a disaster and continue after the disruptive event where the recovery has occurred. Kumar, Poonia [10], among others, have confirmed the Bruneau, Chang [22] resilience component steps, which illustrated different components

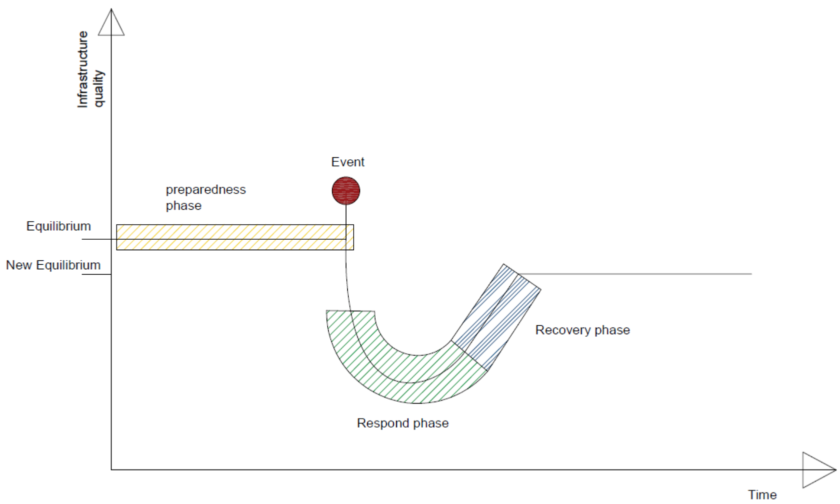

Figure 3: resilience timetable chart; adapted from Bruneau et al. (2003) and Carlson et al. (2012)resilient component study

of resilience through time. He has divided resilience into four main components: preparedness, mitigation, response, and recovery. Figure 3 depicts this resilience timeline. While others, such as [23], claimed that resilience could be divided into three stages: capacity, robustness and recovery.

According to Figure 3, the first phase, preparedness, is related to pre-disaster time. It illustrates how different parts and the overall infrastructure are prepared to face a disaster that might cause damages or disruption to the system's elements or reduce the infrastructure's productivity level. The next stage is the mitigation stage, which indicates the system's capability of reducing the disaster's destructive effect. Response and recovery are the following two stages after a catastrophic event occurs. The response phase is at the early stage of the occurrence of an event, while the recovery stage is a set of actions that will be done in a more extended period.

According to each stage of resilience, different actions should be taken. [24] divided resilience actions into six categories and linked the actions to the resilience components. Figure 4 has summarises the component and action links. An early To cope with the preparedness component of resilience, anticipating the hazard will be helpful. Afterwards, resistance and adsorption are the last actions before the response stage. These two actions occur when we predict and assume that a disaster will occur.

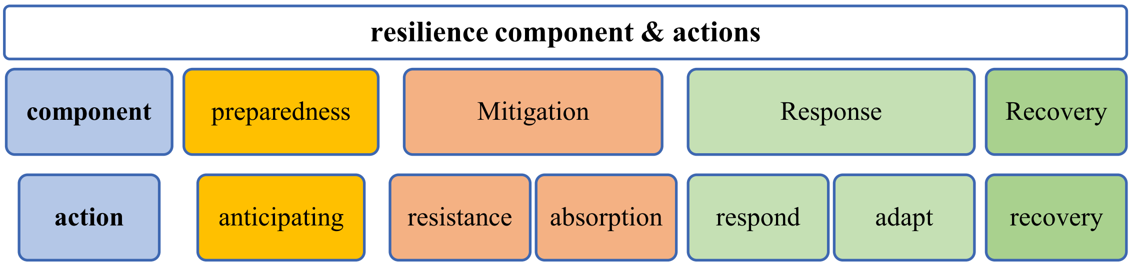

Figure 4: Resilience component and related actions

However, Barker, Ramirez-Marquez [1], [10] provided a more precise timeline for resilience action, which allows resilience actions to consider cascading events in the activity. Figure 5 depicts the resilience action timeline. According to the time frame, the four stages are Reliability, Vulnerability, Survivability, and Recoverability, respectively. The reliability phase is quite similar to the preparedness stage of Bruneau, Chang [22] category, which is related to the time that there is no disruptive event, with a slight difference in evaluation methodologies. Reliability of a system can be defined as the ratio of the system's uptime to the system's uptime plus the system's downtime. The next stage is vulnerability, where the study of the adverse effect on system performance caused by an event is taking place; this is similar to "robustness" in the "resilience triangle" [22]. Finally, recoverability refers to "the speed at which an entity or system recovers from a severe shock to achieve the desired state", similar in concept to "rapidity" in "resilience triangle" discussions [25].

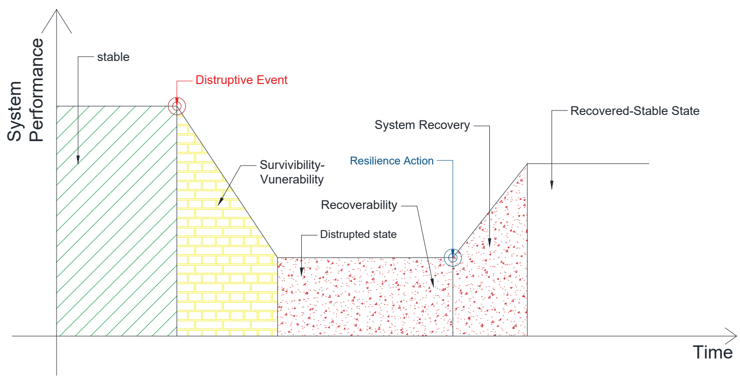

Figure 5: resilience timetable chart; extracted from Barker, Ramirez-

3.4.Resilience Dimensions

Resilience can be evaluated in different aspects. In the context of resilience, the more complex a system, the more aspects should be considered to achieve a resilient system. Therefore, identifying different dimensions of resilience is important. The dimension of resilience is a primary factor in selecting or developing a resilience measurement tool [22].

As infrastructures are one of the most complex systems encompassing various subset components, the dimension of measurement can be categorised in different manners. Table 2 summarises the main infrastructure systems dimensions used in previous research.

Table 2: a Review of different dimensions of resilience

Source	**Dimensions of System**		**Definition**
NIAC [26]	Soft		Related to human requirements and behaviour
	Hard		Relate to the technical abilities of the system
Bruneau [22]	General dimensions	Physical	A group performing a function
		Social	Collaborating groups to perform a function
	Critical dimensions	Technical	The whole systems ability to provide sufficient service
		Organisational	Management capability to deal with disaster
		Social	To minimise the spread of disruption
		Economic	To reduce the losses

As Table 2 shows, Bruneau, Chang [22] have categorised the resilience dimensions through four categories: Technical, Organisational, Social and Economic, known as (TOSE) for infrastructures exposed to a seismic event. This category is one of the most used dimensions to date.

3.5.Features of resilience

Researchers have identified several features of resilience. [27] raised 36 features for resilience. Most of these features are used for community resilience. The intersection of different articles is nine features which by having these features, a system is known to be resilient. According to Figure 6, Robustness,

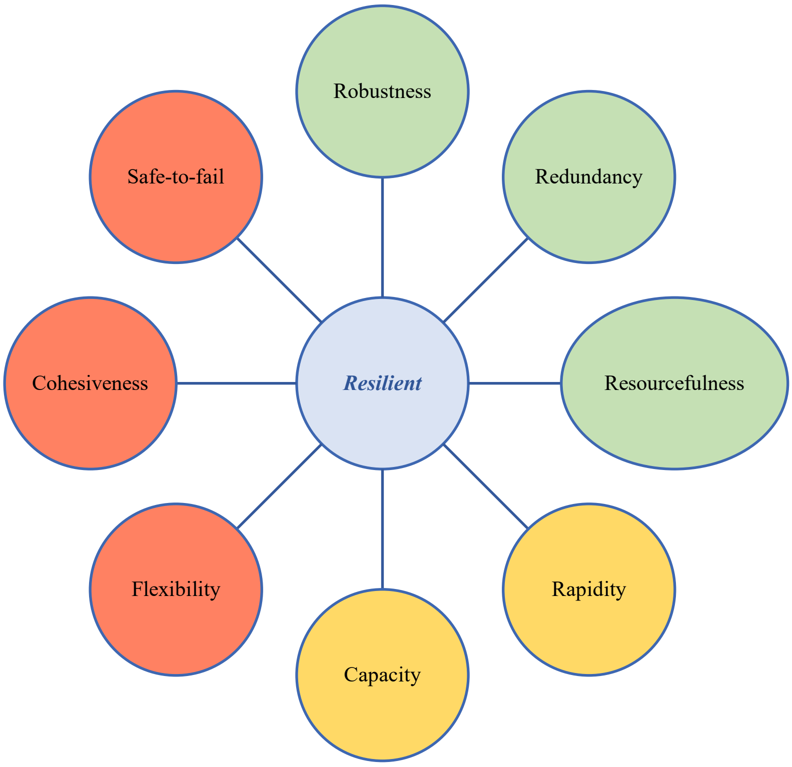

Figure 6: Resilience features in infrastructure systems

redundancy, resourcefulness, rapid recovery, capacity [9], flexibility [28], cohesiveness, and safe-to-fail are the main features of resilience [29].

The resilience features can be categorised into three sections according to the system's failure. The first category includes robustness, redundancy and resourcefulness (Figure 6: Coloured in Green). The next category encompasses rapidity and capacity (Figure 6: Coloured in Yellow). The last group, shown in orange in Figure 6, includes flexibility, cohesiveness and safe-to-fail. This section will briefly illustrate the features of resilience.

Robustness is the ability to endure external stress. A Robust system would not have degradation or loss of function. While redundancy allows the system to change the progress path. But still, the system as a whole will withstand the stress and does not fail.

Resourcefulness is to be ready for a disaster to occur and have the ability to manage the system's performance during the disaster. This feature is crucial since it starts before the event and continues in the reaction phase [30].

Rapidity is defined as the speed or rate at which a system could return to its original state. Although rapidity of recovery allows the system to be disrupted by the time of the disaster, it focuses on the progress priorities to avoid further disruptions in the system. Rapidity shows up in the recovery phase of resilience, and the system must have at least an acceptable functionality after the disaster. The least feature a resilient system should have is capacity. Capacity is the ability to withstand a disaster [31]. In the case of a destructive event such as an earthquake and tsunami, it is known that a resilience infrastructure should have the capacity [32].

Flexibility, tolerance, cohesiveness, and safe-to-fail are the other features of resilience that emphasis the recovery phase of resilience. These features allow the system to fail during a disaster and try to optimise the recovery phase.

4.Discussion

Researchers have shown a high interest in resilience assessment [14, 33]. Each study has based the resilient assessment approach on a different notion. The considered resilience feature, type of action and dimensions would lead to different resilience assessment approach.

Although Hosseini, Barker [34] has claimed a requirement to utilise a standard measuring system for resilient assessments, such a standard intends to compare two similar infrastructures' resiliency in different locations. However, one obvious challenging factor in pedestrian evacuation infrastructures is the inability to compare the resiliency level of different components inside a system. In case of pedestrian evacuation, this resiliency should be evaluated against many indicators, such as road capacity and accessibility, signage visibility, welfare supply during the disaster, supply chain during population displacement and etc. Hence, the evacuation resiliency should be investigated through all indicators and the importance of each element be weighted with accordance to its impact on the overall human survival rate.

The overall solutions to reduce the risk of pedestrian evacuation plans are revolve around the mitigation and response phase of resilience. However, the preparedness role in prevention and tension absorption is neglected in most infrastructure resilience studies.

A city would not have a resilient evacuation plan unless is well prepared for natural disasters and has the ability to withstand the shock it brings to the system. In this manner, it is vital for any evacuation infrastructure to be robust and resourceful and capable toward natural hazards. Although there is a diverse choice for considering resilient features, the most used resilience features for infrastructure sectors in the past decades are robustness and resourcefulness [16, 35]. While the capacity feature of resilience is mostly overlooked in resilience calculations.

In comparison, almost all researchers have constantly considered the technical and organisational dimensions for infrastructure resilience assessment, whereas in evacuation infrastructure although these two terms are the most intensive dimensions, in pedestrian evacuation the human interactions make the system more complicated and brings the social dimension of resilience into account. Unfortunately, most studies have considered either of the dimension. There is a requirement to investigate all terms at once to consider a pedestrian evacuation infrastructure resilient.

5.Conclusions and Further Research

Every investment in evacuation infrastructures must be evaluated from different risk aspects. A critical factor for considering a solution would be the level of resiliency the alteration would bring to the system. Hence, the resilience assessment plays a significant role in decision making, and a unified assessment system might be a help. There is a wide range of resilience parameters to consider in assessment.

This study has outlined different aspects of resilience and analysed what aspects should be considered for assessing pedestrian evacuation infrastructure resilience level. Three aspects of resilience have been considered. The type of action, dimension and feature of resilience choice would significantly affect the resiliency level of an evacuation infrastructure. The results showed that there should be a comprehensive study to evaluate all aspects involved in a pedestrian evacuation and make a standard measurement to be able to compare the resiliency level of elements.

Future research will explore the resilient assessment measure and approach. Also, experimentation will be considered on a set of case studies related to a real-life evacuation scenario and considering various metrics to evaluate the change in resilience levels for considering improvements to the evacuation infrastructures in their long-term strategic plans.

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