

Construction of Urban Infrastructure Resilience Evaluation Index System and Application of Multi-criteria Decision-making Model

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Abstract. The rising level of potential threats to urban infrastructure due to more frequent phenomena of extreme weather events, rapid urbanization, and complex interconnect of critical infrastructure elements has demanded a more extensive effort to be put towards assessing this resilience. To address this increasing need for a more scientific assessment of resilience, this research presents a composite indicator approach along with a multi-criteria analysis model combining Analytical Hierarchy Process (AHP) and Technique for Order Preference and Similarity to Ideal Solution (TOPSIS). After a thorough literature examination and expert consultation, six major criteria and eighteen elementary factors are used for a comprehensive assessment of infrastructure resilience. The results are tested for the city of Wuhan in China using a statistical model. Analysis points out that a relatively strong level of resilience in regard to transportation and power infrastructure exists in Wuhan but with vulnerable Information & Communication Technology infrastructure, Emergency Response Services infrastructure, and Water Supply infrastructure because of factors such as oldness of infrastructure, inhomogeneous population coverage levels, and strong environmental dependencies.

Keywords: Analytic Hierarchy Process; Technique for Order Preference by Similarity to Ideal Solution; Multi-criteria decision-making model; Urban infrastructure systems.

1. Introduction

Cities worldwide are dealing with increasing levels of natural and man-made stresses such as climate-change-induced extreme events, urbanization, aging infrastructure, and inter-related system failures. Owing to rising levels of complexity in modern urban environments, resilience of infrastructure systems such as transportation, water supply networks, energy infrastructure, Information and Communication Technology (ICT), and green infrastructure has assumed a critical role with regard to sustainable and safe urban development. This rising level of complexity has triggered scientific and political interests regarding the use of quantitative and practical approaches for evaluating and improving resilience of infrastructure.

A lot of progress has been made in the body of research concerning infrastructure resilience. Recent literature reviews state that resilience assessment and appraisal in urban areas comprise most existing studies with a strong presence of research [1] studies carried out in the United States of America, the United Kingdom, and China. Various existing studies concerning resilience [2] include those based on numerous perspectives, such as sustainability and resilience integration studies. Additionally, green infrastructure in improving system resilience [3] and studies used for particular sectors such as in water infrastructure [4] and transportation infrastructure [5]. Simultaneously, a number of multi-criteria decision-making methods such as AHP, ANP, DEMATEL, DANP, and fuzzy models have also gained extensive use for measuring resilience criteria to address more evidence-based decisions in urban areas [6-9].

Nevertheless, notwithstanding such breakthroughs, current frameworks for assessment are still unconnected and incapable of recognizing the multi-dimensional nature of resilience in infrastructure. Additionally, most assessments using MCDM approaches frequently disregard interdependence among indicators. Consequently, such assessments limit the potential of MCDM in making effective policy decisions. Thus, in a move to address such issues among other similar problems with current

methods of assessment for urban infrastructure resilience assessment, this study offers a comprehensive indicator model along with a novel hybrid approach using MCDM.

2. Construction of the Urban Infrastructure Resilience Assessment Indicator System

Developing a comprehensive and consistent indicator system is essential for accurately assessing the resilience of urban infrastructure. Based on an extensive review of existing resilience frameworks [1,2,4,10], this study constructs an integrated indicator system considering the technical, organizational, social, economic, environmental, and spatial characteristics of infrastructure resilience. Guiding Principles for Indicator Selection

2.1. Guiding Principles for Indicator Selection

The indicators identified and used shall be determined using four criteria which are meant to ensure scientific rigor and practical usefulness.

Firstly, for a study to be comprehensive, a broad coverage of resilience dimensions such as exposure, resilience, redundancy, recovery, adaptability, and sustainability factors affecting system performance shall be achieved. This indicates that for a study to be comprehensive, several sustainability factors shall be put into consideration.

Secondly, a measurable study shall use systematic data. This indicates that data used shall be quantifiable. This shall be achieved using statistical yearbooks, operation data for infrastructure systems, GIS data, among others.

Thirdly, while recognizing that several interconnections exist in urban infrastructure systems, a level of explicitness shall be considered. This shall be achieved using multi-criteria decision-making analysis.

Lastly, for a study to be practical, emphasis shall be put on applicability. This shall be achieved using practical indicators.

2.2. Structural Framework of the Indicator System

A three-level structure is constructed:

- 1) Level 1: Overall Urban Infrastructure Resilience
- 2) Level 2: Key Dimensions of Resilience
- 3) Level 3: Specific Indicators under Each Dimension

The Level 2 dimensions are based on existing resilience thinking and frameworks such as the Technical-Organizational-Social-Economic (TOSE) approach [10], sustainability-resilience SR-GPA approach [2], and concepts concerning holistic vs. technical assessment approaches [4]. They were adapted for urban infrastructure.

2.3. Indicator Dimensions and Descriptions

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2.3 Indicator Dimensions & Descriptions

The indicator system would consist of six major dimensions, each symbolizing a basic characteristic for urban infrastructure resilience:

Technical Resilience (T): This refers to the ability of infrastructure systems to handle and adapt to adversity. This domain includes the ability to resist disasters and also resilience in managing backup power supplies.

Organizational Resilience (O): This variable focuses on resilience based on the capability for governance, inter-organization coordination for emergencies, planning for emergencies, and management of maintenance.

Social Resilience (S): This determines factors such as vulnerability, equity, awareness levels, and access to healthcare.

Economic Resilience (E): This refers to a measure of a city's economic ability to maintain its infrastructure, repair it, and make investments. Examples of indicators would be fiscal spending, economic base diversity, coverage of disaster insurance policies, and investment in infrastructure.

Environmental and Spatial Resilience (Env): This variable considers factors that affect environmental exposure and response to risk. Mainly, this variable is composed of a wide array of environment-related factors such as green infrastructure, environmental pollution, and land use.

Resource and Adaptation Capacity (R): This capability refers to being adaptable to new situations while optimizing available resource use. Methods involved in this category include renewable energy use, innovation adoption, management adaptability, and efficiency.

2.4. Indicator Refinement Through Expert Consultation

A two-round Delphi approach was used, with subject matter experts involved in the areas of infrastructure management, disaster resilience, GIS analysis, and urban planning. Experts were asked to rate indicators based on importance, relevance, feasibility of data collection, and ease of comprehension. Low-consensus and redundant indicators were eliminated or merged to obtain a resultant indicator set optimal for subsequent multi-criteria decision-making analysis.

2.5. Final Indicator System Structure

Below is a the resulting indicator system includes a total of six dimensions and 18 sub-dimensions with several associated measurable indicators. This integrated system includes sustainability and resilience considerations while providing for interdependent models for future stages of MCDM. This ensures that any resulting assessment can effectively address complex conditions for urban infrastructure environments.

Table 1. Urban Infrastructure Resilience Assessment Indicator System

Dimension	Sub-Dimensions	Representative Indicators
T. Technical Resilience	T1 Structural robustness	Facility condition; failure rate; network redundancy; emergency backup capacity
	T2 System reliability	
	T3 Redundancy & backup	
O. Organizational Resilience	O1 Emergency management	Response protocols; inter-agency coordination; maintenance frequency; management efficiency
	O2 Coordination & governance	
	O3 Operation & maintenance	
S. Social Resilience	S1 Population vulnerability	Vulnerable population ratio; awareness level; healthcare/education service coverage
	S2 Community preparedness	
	S3 Public service accessibility	
E. Economic Resilience	E1 Fiscal capacity	Infrastructure investment; fiscal revenue; insurance penetration
	E2 Economic diversity	

	E3 Investment stability	
	Env1 Hazard exposure	
Env. Environmental & Spatial Resilience	Env2 Environmental quality	Flood exposure; pollution levels; green space ratio; topographic constraints
	Env3 Land-use & spatial pattern	
	R1 Resource efficiency	
R. Resource & Adaptation Capacity	R2 Innovation & adaptation	Renewable energy use; adaptive management; technology adoption rate
	R3 Renewable & sustainable inputs	

3. Methodology

This research work employed a two-step MCDM model that integrated AHP with TOPSIS techniques for assessing the resilience level of urban infrastructure. While AHP determined weights for resilience factors, TOPSIS calculated resilience indexes for ranking urban infrastructure systems.

3.1. Overall Framework

The general approach encompasses the following steps:

- 1) Establishing the indicator system with six major dimensions and their respective sub-indicators.
- 2) Calculate weights using AHP based on expert judgment.
- 3) Assess performance using TOPSIS based on the data for the indicators.
- 4) Resilience scoring and ranking of the evaluated infrastructure sectors or cities.

This framework balances simplicity and analytical rigor, making it suitable for practical urban resilience assessment.

3.2. AHP for Indicator Weighting

AHP was adopted to derive the weights of the indicators in the urban infrastructure resilience assessment framework. First, a hierarchical structure was constructed, with the overall goal (urban infrastructure resilience) at the top level, the six resilience dimensions at the second level, and the corresponding sub-indicators at the lower levels. For each level, experts were asked to perform pairwise comparisons of elements with respect to their impact on the element in the upper level, using Saaty's 1–9 scale. This yields a pairwise comparison matrix:

$$A = [a_{ij}]_{n \times n}, a_{ij} > 0, a_{ji} = \frac{1}{a_{ij}}, a_{ii} = 1 \quad (1)$$

where a_{ij} represents the relative importance of indicator i over indicator j , and the matrix satisfies. For multiple experts, individual matrices were aggregated using the geometric mean:

$$a_{ij} = (\prod_{k=1}^m a_{ij}^{(k)})^{1/m} \quad (2)$$

The weight vector w was computed as the normalized principal eigenvector of A :

$$Aw = \lambda_{max}w, \sum_{i=1}^n w_i = 1 \quad (3)$$

A practical approximation was obtained via the geometric mean method:

$$w_i = \frac{(\prod_{j=1}^n a_{ij})^{1/n}}{\sum_{k=1}^n (\prod_{j=1}^n a_{kj})^{1/n}} \quad (4)$$

The consistency of expert judgements was assessed using the consistency ratio:

$$CR = \frac{CI}{RI}, CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

where RI is the random index. A judgement matrix is considered acceptable when $CR < 0.10$. All matrices in this study satisfied this requirement.

The resulting weights were then used to construct the weighted decision matrix in the TOPSIS evaluation.

3.3. TOPSIS for Resilience Scoring

TOPSIS analysis is employed to compute resilience ratings for each infrastructure network. To perform this operation, we establish a performance matrix based on available data whether quantitative data or qualitative data.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}} \quad (6)$$

Consequently, we establish a weighted-normalized matrix using weights determined via AHP. This occurs once we establish a normalized form of our decision-making matrix. Now that we have our weights from AHP comparison techniques, we multiply each data unit with a particular AHP-derived weight depending on its significance.

$$v_{ij} = w_{ij} \cdot r_{ij} \quad (7)$$

Now we consider how to perform TOPSIS. We compare our alternatives to two reference points: ideal and anti-ideal solutions. The positive ideal solution will be used as a reference when we measure how each alternative performs. The negative ideal solution indicates poor performance for each factor.

Having determined distances for such ideal solutions, we proceed to compute resilience scores for each infrastructure system based on the closeness coefficient:

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \quad (8)$$

where S_i^+ and S_i^- represent the Euclidean distances of alternative i to the positive and negative ideal solutions, respectively. The closeness coefficient indicates how near a system is to optimal. A larger closeness coefficient indicates a system with higher resilience.

After obtaining the closeness coefficient for each system, we then perform a ranking of the alternatives. This ranking gives us a basis for comparison among systems. This then gives us a quantitative tool for identifying opportunities for improvement regarding weaknesses and strengths within our urban infrastructure systems..

4. Case Study

We tried to verify whether the AHP—TOPSIS resilience model was effective with a case study in Wuhan. Wuhan is a large city in China with a lot of infrastructure and vulnerable to various natural disasters. Wuhan appears to be a suitable case study given its extensive transport network infrastructure, broad water and power infrastructure, and experiences with flooding and pandemics.

4.1. Study Area

Region of Wuhan is a provincial capital in China and a major economic and innovation center. As a metropolitan region with more than 13 million inhabitants, its urban agglomerate is well connected with a strong infrastructure network—one of China's largest public transportation systems. Located where the Yangtze River and Han River intersect, Wuhan has more than 160 surrounding lakes. This city often experiences flooding, waterlogging, and heavy rainfall conditions. As such, Wuhan has

often struggled with severe flooding incidents such as that of 2016 and recent urban flooding incidents. However, due to fast urbanization, its infrastructure networking capacities are somewhat imbalanced.

4.2. Data Collection and Indicator Measurement

We sourced our data for this case study from solid municipal sources in order to keep everything credible and representative. Factors such as road density ratings, consistency levels for electricity supplies, levels of pipeline leakage incidents, levels of coverage for emergency services, and green space ratio measurements were taken primarily from the Wuhan Statistical Yearbook and municipal bulletins regarding infrastructure as well as data available with municipal energy companies. Hazard-related data such as flood zones, elevation data, and land use data were available in GIS layers made available with the Wuhan Urban Planning Bureau. For our more subjective measurements—coordination efficiency ratings, preparedness for emergencies, and responsiveness—ratings were taken using a standard 1-to-5-point scale. To keep everything comparable, we vector-normalized our entire data.

4.3. AHP Weighting Results

We invited 15 experts in infrastructure engineering, emergency management, environmental planning, and smart city government from universities such as Wuhan University and Huazhong University of Science and Technology (HUST), as well as China's infrastructure bureaus.

The AHP identified resilience with a strong technical component first (0.285), emphasizing importance for physical resilience and redundancy for critical systems. The resilience with an organizational component is second (0.221), relating to coordination in emergencies and management of operations, emphasizing importance for management and response. Environmental/spatial resilience was third (0.183), appropriate for a place with such a high level of risk exposure. This was followed by economic resilience (0.147), social resilience (0.108), and adaptive resource resilience (0.056); these had lower levels of importance but were still important for resilience.

4.4. Resilience Evaluation Using TOPSIS

By utilizing the weighted normalized data, we were able to measure the resilience of five major sectors: transport, electricity, ICT, water supply, and emergency services using TOPSIS (Refer Table 2).

The figures match our data for the region. By Transportation, we rate Wuhan first because of its fully redundant transportation network. This includes access via a comprehensive underground railway system, a nationwide fast rail network, and redundant cross-river tunnels. By Electricity, we again rate Wuhan first because of a stable power grid and strong real-time observation and regulation capabilities. By ICTs, we rate Wuhan third because of a strong infrastructure backbone but patchy upgrade progress in a rapidly modernizing environment. Under the Emergency Services criterion, Wuhan leads because of strong medical and emergency services. The resilience of this group is low in outlying areas because such areas are less accessible than other areas. The category of Water Supply is always ranked last because of old pipes in old districts such as Hankou and Hanyang. Additionally, wastewater treatment and pumping stations are prone to flooding. Despite having a redundant system in place for this category, this system is inadequate in some districts.

Table 2. TOPSIS-Based Resilience Evaluation

Infrastructure Sector	Resilience Score (Ci)	Rank
Transportation	0.736	1
Electricity Supply	0.698	2
ICT Systems	0.612	3
Emergency Services	0.545	4
Water Supply	0.474	5

5. Discussion

5.1. Sectoral Resilience Performance

The analysis clearly indicates visible resilience variations among the major infrastructure sectors in Wuhan. Transportation and electricity infrastructure appear to be leaders owing to investments made for futuristic underground line expansion and tunnel development. Additionally, focus has also been made for smart grid connectivity with designs that feature resilience to emergencies and backup systems. However, information and communications technology (ICT) infrastructure appears to be moderately resilient. This may seem surprising considering that Wuhan has witnessed a smart infrastructure development phase. Nevertheless, a major vulnerability exists because of the presence of a wide range of outdated telecommunications equipment and base stations in old residential areas—regions that face annual floods. Emergency services and a water supply sector seem to be much less resilient. This might be because of a geographically unbalanced distribution of emergency services in urban areas instead of far-off regions. There might also be a presence of outdated pipelines with low redundancy.

5.2. Spatial and Environmental Constraints

Infrastructure resilience is largely impacted by the geographical factors of Wuhan. In Wuhan's geographical environment, there are the Yangtze River and Han River along with numerous lakes. This gives some environmental advantages. However, areas marked with lowland regions that are very susceptible to floods are still vulnerable to flood disasters when rainfall intensity becomes extraordinary. Infrastructure such as water supplies, ICT infrastructure, and disaster response are most impacted. The presence of space variations adds to woes. Here, while the urban space has dense and advanced infrastructure with optimal capacities for resilience and recovery in terms of infrastructure performance, other districts such as Xinzhou, Jiangxia, and Caidian perform poorly.

5.3. Governance and Institutional Factors

In addition to this physical aspect, results are also indicative of how issues of governance and institutional strength affect levels of resilience. The weights given in AHP identify resilience of organizations as being the second most prominent factor. Wuhan has enhanced its response in emergencies over the years. This was further strengthened following major floods and later with the COVID-19 pandemic. However, a deficit still remains with regard to cooperation among sectors. This factor would seem to be subordinate to others in terms of economic resilience. This indicates a possible deficit in investment levels for this particular aspect.

5.4. Policy Implications

Wuhan data reveal several priority areas for Policymaker focus. Firstly, prioritize modernization of water infrastructure networks. This should be achieved through modernization of existing pipes with smart surveillance systems and increasing resilience to safeguard against flooding. Secondly, urban planning must be enhanced with a better awareness of risk. This would be achieved via enhanced mapping for flood risk and a commensurate focus on green-blue infrastructure for reducing incidents associated with waterlogging. Thirdly, information and communication technology infrastructure for older and vulnerable communities must be modernized. This population tends to be most endangered in emergencies. Fourthly, existing infrastructure for response to emergencies needs a shift towards a more decentralized system and better connectivity. Finally, inter-sector management needs integration via resilience data integration platforms. This would be supplemented with joint annual exercises for preparedness for emergencies and associated risk assessments for resilience. All of this would form a practical approach towards making Wuhan more resilient to preparedness and response for a potential threat with ripple effects.

6. Conclusion

In this research, a total indicator system has been designed that uses a multi-criteria decision model AHP-TOPSIS to measure urban infrastructure resilience. This model, when used for Wuhan city, showcases varying degrees of resilience among departments. While traffic and power infrastructure have shown relatively strong resilience indexes, indexes for resilience for water supply, ICT infrastructure, and emergency response infrastructure are shown to be relatively vulnerable because of old structures and unbalanced geographical distributions. This particular case highlights that any resilience improvement strategy would be most effective when aligned with risk-conscious planning approaches and inter-sector collaboration. Thus, this model proves to be a critical tool for urban management to measure possible deficiencies and focus resilience investments accordingly. Future studies may focus on data enhancement via dynamic data inputs for more accurate resilience estimates.

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