ASSESSING THE RESILIENCE OF INDUSTRIAL AREAS FROM THE PERSPECTIVE OF URBAN RESILIENCE AND COMMON-POOL RESOURCES: THE CASE STUDY OF TAIWAN

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Abstract. Industrial development is a critical factor for the economic development of a country. This study applies the fuzzy Delphi method (FDM) and a dynamic analytic network process (DANP) to develop a tool for the assessment of the resilience of industrial areas in Taiwan from the common-pool resources (CPRs) perspective to enhance the resilience of industrial areas and also ensure the efficient use of common urban disaster prevention resources. This study is innovative and may facilitate the assessment of the resilience of industrial areas and the validation of interactions between urban resilience, industrial area resilience and CPRs. The influencers of the resilience of industrial areas can be categorized into 5 dimensions and 24 indicators. The five dimensions are vulnerability, urban environment, industrial environment, factory properties, and governance and adaptation. The governance and adaptation dimension is the most crucial, and the five indicators with the highest weights are emergency response and planning, management organization, supervision, employee awareness of disaster prevention, and industry type. The results indicate the importance of adaptation and governance and response to the importance of Ostrom's (2005) CPRs. The study can be used as a reference for countries assessing the resilience of industrial areas and developing adaptation strategies.
Keywords: *resilience assessment, resilient adjustment indicators, fuzzy Delphi method (FDM), dynamic analytic network process (DANP), resilience governance*

Introduction

In recent years, climate change has increased the frequency and severity of extreme weather events such as heavy precipitation, storms and floods (Heinzlef et al., 2020). Resilience research has become essential for disaster management, sustainable development, and urban planning under conditions of extreme global climate and environmental change. In the 1970s, studies on resilience have emerged in the field of disaster vulnerability. The term resilience originally referred to the ability of an ecosystem to recover from an external shock or disturbance to its preshock state (Holling, 1973, 1996; Timmerman, 1981). However, over time, the term also came to refer to the ability of a city or society to learn to reorganize to improve its adaptability to external shocks or disturbances and to develop local adaptability and innovations through organizational studies (Brunetta et al., 2018; Cashman, 2011).

The relationship between resilience and vulnerability has been a major focus of academic discussions on resilience research. Although scholars of disaster adaptation have regarded resilience as a component of vulnerability (Timmerman, 1981), some scholars have argued that the two are intertwined socially and spatially, and one cannot be subordinate to the other (Buckle et al., 2001). The two concepts should be

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integrated in analyses, and a collaborative approach to external environmental change should be adopted to develop new adaptive capacities (Miller et al., 2010; Turner, 2010). The 2001 AR3 report of the Intergovernmental Panel on Climate Change (IPCC) included adaptive capacity as a proxy for resilience in its definition of vulnerability (IPCC, 2001). The IPCC's AR5 report of 2014, however, distinguishes between resilience and vulnerability and indicates that resilience involves interactions between the biological environment, social conditions, institutions, and adaptation strategies (IPCC, 2014). Moreover, the report states that resilience should cover socioeconomic conditions, adaptive capacity, resilience, and learning capacity (Keck and Sakdapolrak, 2013).

The perspectives adopted in research on resilience encompass the natural environment, the socioeconomic environment, types of disasters, and various spatial scales (Adger, 2006). Because industrial development is an integral aspect of national and urban economic development, disasters caused by climate change or human negligence may lead to a loss of equipment and personnel, disruption of services and supply chains, unemployment, or labor shortages (Khazai et al., 2013). However, disasters may also lead to economic ripple effects, affecting not only a single company or firm but also upstream and downstream industries outside the affected area. Disasters may even affect regional and national economic development (Okuyama, 2004; Tierney, 2007). The 2011 earthquake in northeastern Japan affected the automotive, petrochemical, and semiconductor industries. The disaster caused a shortage of raw materials and critical components for upstream and downstream industries, which significantly affected the global supply chain.

Because of its geographical location, topography, and geological characteristics, Taiwan is an Asian country with frequent earthquakes and typhoons. The scale and frequency of its disasters are increasing because of climate change, as exemplified by several major disasters. Industrial areas in Taiwan are primarily distributed near or within urban areas, as is true of many other Asian countries, such as Japan, South Korea, and Singapore. The spillover effect from disasters can endanger surrounding residential and commercial areas and lead to damage throughout a city (Chang and Falit-Baiamonte, 2002). Therefore, improving the resilience and adaptability of industrial areas is essential for reducing the impact of disasters in urban and industrial areas. Because industrial areas are located close to or within cities, assessments of industrial areas' resilience should not only include the industrial areas themselves but also consider the interactions between industrial areas and cities and the resilience resources that can be shared between them (Chelleri, 2012; Coaffee et al., 2018). Additionally, the resilience of industrial areas should be assessed from four perspectives: prevention, renewal, recovery, and repositioning (Holm and Østergaard, 2015). Urban areas are places of human activity and comprise a socio-ecological-economic system of inhabitants, land use, industrial development, and transportation (Boyd and Juhola, 2015). Urbanization further affects urban exposure and vulnerability to extreme events, increasing the risk to urban areas (Heinzlef et al., 2020). Urban resilience emphasizes resource identity, actor identity, resource ownership, and organization and can be used to establish governance mechanisms through resource integration. Urban resilience is, therefore, a more strategic, integrated, and forward-looking concept than risk management, disaster prevention, and mitigation (Ruan et al., 2021).

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Industrial areas are a part of a city, and when discussing the resilience of industrial areas, urban resilience must also be considered. In facing, handling, and adapting to disasters, manufacturers and industrial areas must use not only their own resources but also the resources of the entire city, including its infrastructure, disaster prevention facilities and information, networks, and disaster avoidance spaces. Ostrom (1990, 2009) developed a socio-ecological-economic system framework for resource systems, users, and governance systems that was based on the concept of common-pool resources (CPRs). Ostrom suggested that only through a CPR governance model and cooperative relationships among resource users can effective resource use be achieved and the tragedy of the commons avoided (Hardin, 1968). To maximize the use of shared resilience resources in urban and industrial areas, this study incorporates CPRs into an assessment of the resilience adjustment indicators for industrial areas. Additionally, industrial areas in Taiwan are developed by both the government and the private sector; the government has a management unit that is responsible for disaster prevention and restoration, and individual manufacturers often develop private industrial areas. Therefore, this study investigates whether the government is an essential factor affecting the resilience of industrial areas. The contributions and novelty of this study are summarized in the following.

Interactions between urban resilience and industrial area resilience

Resilience research has shifted from focusing on large-scale national and regional contexts to small-scale contexts such as communities, watersheds, and specific land uses. However, studies must acknowledge that large-scale spaces possess the resilience resources required by small-scale spaces and that the two are mutually dependent on and interact with one another. In this study, the resilience of industrial areas is explored from the perspective of urban resilience, and the interactions between the two are analyzed with consideration of the fact that most industrial areas in Asian countries are located near urban areas and disasters in industrial areas may affect the surrounding urban areas.

Establishment of indicators of adaptive resilience in industrial areas from the perspective of shared economic resource governance

According to urban resilience research, industrial areas may use some urban resilience resources to enhance their resilience and adaptability. Such shared resources are susceptible to the tragedy of the commons because free-riding can lead to the inefficient use of resources. The present study incorporates CPRs (Ostrom, 2009) as an indicator of adaptive resilience in industrial areas, with the efficiency of resilience resource use maximized through cooperation among resource users.

Research contribution

No study has yet analyzed the indicators of industrial area resilience from the perspectives of urban resilience and CPRs. In this study, the fuzzy Delphi method (FDM) was first used to identify critical indicators through a questionnaire administered by experts. Additionally, this study considers the relationship between adaptive resilience indicators for urban and industrial areas and uses decision-making trial and evaluation laboratory (DEMATEL)-based analytic network process (ANP), hereafter DANP, to present the network interactions between the indicators. The framework of this study is presented in *Figure 1*.

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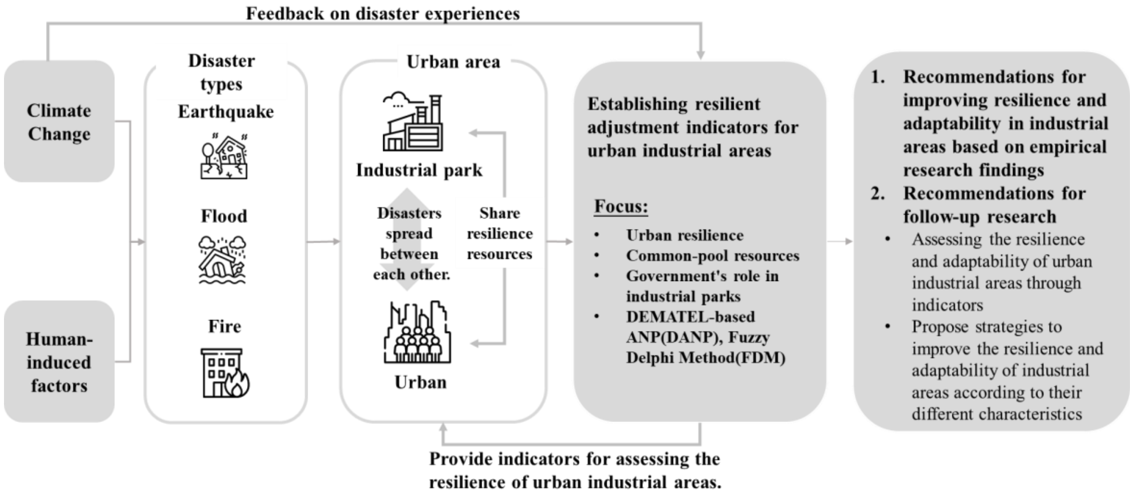

Figure 1. *Research framework*

This article aims to establish a quantitative model for assessing the adaptive capacity of industrial zones in terms of urban resilience and common-pool resources (CPR) and to verify the interactive relationship between urban resilience, industrial zone resilience, and CPR. The evaluation indicators can be a reference for industry regulators or companies to assess their resilience adaptation capabilities and propose improvement strategies. The goal is to effectively use resilience resources among urban areas, industrial zones, and various companies through resilience governance. The first section presents an introduction to this study, and the second section presents a literature review on urban resilience, industrial area resilience, and shared resources and summarizes the variables that affect the resilience of industrial areas to establish a hierarchical analysis framework of impact areas and indicators. The third section introduces the types and characteristics of industrial areas in Taiwan. The fourth section presents an analysis of the empirical results and includes the results of FDM and DANP analyses, the development of an assessment framework for and indicators of the resilience and adaptability of industrial areas, a discussion of the empirical results of this study, and recommendations for developing disaster adaptation strategies. Finally, the fifth section provides a conclusion.

Review of literature

Urban resilience

Resilience was first applied in relation to the single stability of engineering systems, which was considered to indicate the reliability of a system (Alfredo and Wilson, 1984). The scope of the concept was gradually extended to include ecological and ecosystem resilience (Holling, 1973; Berkes et al., 2008). Social ecosystems are closely related to social functions. The resilience of socio-ecological systems (SESs) involves the process by which SESs continuously adapt to achieve sustainable development, and the concept has been widely applied and debated in the social sciences. According to research on the resilience of SESs, social resilience can enable a social system to be maintained in an ideal state and enables it to adapt to change and absorb stress, which is essential for

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sustainable development (Adger, 2000). The International Strategy for Disaster Reduction holistically defines resilience as the ability of a system, community, or society to cope with or adjust to a disaster. Moreover, it indicates that resilience can be determined by how a social system is organized and adapts to disasters (Habitat, 2018).

Cutter et al. (2008) proposed the disaster resilience of place model as a quantitative indicator for resilience assessment. The model considers the internal factors for resilience of a place to be indicators of existing conditions, mitigation measures, response capacity, resilience, and adaptation. The external resilience indicators of this model are disaster characteristics (e.g., frequency, quantity, and duration) and intensity. Buckle et al. (2001) suggested that resilience assessments be analyzed from an integrated perspective to ensure the full extent of resilience, including the aspects related to disaster resilience, disaster emergency response, warning and evacuation, risk knowledge, land use and design, resilience resource management, socioeconomic status, and governance, is considered to address deficiencies in resilience assessments. In the AR5 report, the IPCC (2014) defined resilience as the ability of a system to absorb disturbances, maintain basic operations, reorganize, adapt, learn, and transform. The report also described the relationship between resilience and vulnerability separately to emphasize the importance of resilience.

The scope of research on resilience has expanded to include the natural environment, the urban environment, and different spatial scales (Adger, 2006). Douglass (2016) determined that such research should include the spatial scales of neighborhoods, the urban environment, and transborder riparian regions. In 2015, the United Nations included resilient cities in their sustainable development goals and announced the goal that cities worldwide become sustainable by 2030. Urban resilience involves the ability of cities to remain structurally and functionally unchanged when disturbed by external factors and to recover from challenges and disruptions (Coaffee, 2013; Wagner and Breil, 2013; Desouza and Flanery, 2013). Urban resilience has four dimensions: metabolic flows, governance networks, social dynamics, and built environment. Metabolic flows involve the relationships between production, supply, and consumption chains; governance networks involve institutions and institutional structures and organizations; social dynamics involve human capital and equity concerns; and built environment involves the ecosystem services in urban environments (Chelleri, 2012; Coaffee et al., 2018). Ribeiro and Gonçalves (2019) reported urban resilience is applied to five main areas of research, namely changing climate conditions, urban planning, urban communities, energy, and disasters (both natural and manufactured). Moreover, they reported that urban resilience assessments should integrate predisaster natural environmental conditions, built environment conditions, socioeconomic conditions, disaster vulnerability conditions, and an urban system’s ability to adapt and learn from postdisaster resource use (Füssel, 2007).

Urban resilience can be developed in five areas: urban governance, urban planning and environment, resilient infrastructure and essential services, urban economy and society, and urban disaster risk management (UN-Habitat and DiMSUR, 2020; *Fig. 2*). Urban governance emphasizes the relationship between citizens and local governments and the participation of all stakeholders in public policy under sound laws, policies, and administrative structures. Urban planning and environment encompasses urban planning and design, the quality of the natural environment, public and green spaces, and other factors related to climate change. The area of resilient infrastructure and essential services emphasizes the importance of ensuring equal access to all infrastructure and

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essential services in the face of shocks and pressures. The area of urban economy and society encompasses industrial development, household income growth, and social inclusion. Finally, disaster risk management emphasizes cooperation between local governments, communities, and relevant organizations to enhance the capacity of cities to face natural or artificial disasters, adapt to address disasters, and recover quickly from disasters.

Figure 2. *Components and indicators of urban resilience. (Source: UN-Habitat and DiMSUR, 2020)*

Boyd and Juhola (2015) argued that urban resilience should be developed by incorporating disaster prediction, disaster response, and postdisaster reconstruction into urban resilience planning through urban policy. This would enable future disasters to be prevented and the urban characteristics of a city to be defined. Additionally, urban resilience is influenced by the types of resources involved; the characteristics of actors; the ownership and organization of resources; and the establishment of governance mechanisms to integrate resilient resources, which is known as resilient governance (Vale, 2014). As previously mentioned, cities are places of human activity, and humans are vital drivers and recipients of environmental change (Boyd and Juhola, 2015). In response to Vale's report on resilient governance (2014), Mehmood (2016) argued that cities must be prepared, sustained, transformed, and adapted to ensure they can evolve through learning, innovation, and resilience in the face of complex socio-ecological-economic systems.

The present study considers the aforementioned aspects and indicators of urban resilience assessment, including the physical urban environment, infrastructure, disaster management, industrial development, and governance, to be essential for developing resilience assessment indicators for industrial areas.

Resilience of industrial areas

Industrial development is an essential element of a country's economic development; thus, losses caused by both natural and artificial disasters can affect not only the development of relevant industries (Khazai et al., 2013) but also the overall economic development of a region or country (Okuyama, 2004; Tierney, 2007). Tiwari and Premi

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(2016) argued that industrial areas are at high risk of experiencing disasters because disasters can spread rapidly and cannot be easily stopped in urban areas. Therefore, the resilience of industrial areas must be addressed to prevent large-scale disasters in urban areas (Pendallet al., 2010).

Industrial areas in Asian countries (including Taiwan) are located in or near urban areas. They are home to various industry manufacturers that cooperate and compete to form industrial clusters (Chen et al., 2019; Khazai et al., 2013).

The resilience adaptation capacity of industrial areas must include the external urban resilience capacity and the internal environmental characteristics of industrial areas. As described in the “Urban resilience” Section, the internal influences on the resilience of an industrial area include the physical environment and the characteristics of firms, employees, industrial organizations, disaster response organizations, and government involvement (Tierney, 2007; Zhang et al., 2009; Di Tommaso et al., 2023). The resilience of an industrial area is influenced by whether it has sufficient space for disaster preparedness, roads, and equipment. Moreover, resilience is affected by the coverage of disaster response organizations; mutual support networks among neighboring communities, cities, or other industrial areas; and awareness of disaster preparedness (Khazai et al., 2013; Chen et al., 2019). Regarding manufacturers, their size, capital, staff characteristics, organizational networks, and product diversity affect their resilience (Chang and Falit-Baiamonte, 2002; Khakzad et al., 2016; Lo et al., 2019; Di Tommaso et al., 2023). Large-scale manufacturers usually have more funds, human resources, and network resources to cope with various disasters than small-scale manufacturers do (Chang and Falit-Baiamonte, 2002; Khakzad et al., 2016). The socioeconomic characteristics of employees, including their education level, age, income, and gender, are also factors that influence resilience. The impact of a disaster can be reduced through flexible production strategies, and government intervention can significantly affect adaptive resilience (Lo et al., 2019). Such influences are used as a reference in the present study to develop indicators.

Common-pool resources CPRs

The common-pool resources (CPRs) involve a system of natural (e.g., ecological resources) and artificial (e.g., public infrastructure) resources that, because of the vast scope of these resources, leads to more people being able to use resources and reduces the stock of the resource. However, CPRs can be costly if the potential beneficiaries of resource use are excluded in the CPRs (Ostrom, 1990). This type of commons may prevent potential beneficiaries from using CPRs. Hardin (1968) introduced the concept of the tragedy of the commons as involving redefining the property rights of the commons, internalizing external costs, using a price mechanism to regulate costs, or introducing government intervention through national legislation. However, Ostrom (1990) argued that the inefficiency of the commons dilemma does not necessarily stem from self-interested CPR users but rather can be addressed by promoting the autonomy and growth of institutions that regulate the autonomous management of CPRs and share their benefits. Ostrom (1990, 1995) also argued that the autonomous management of shared resources occurs when resource users have a wealth of indigenous knowledge about resource use. Additionally, close proximity and monitoring of noncompliant users and the use of social networks to impose sanctions on noncompliant users (Dixit et al., 2009) can be advantageous in that it can, for example, reduce government administrative costs.

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Ostrom (1990) identified three areas that must be addressed for effective CPR governance: the provision of a new system, mutual trust and commitment, and mutual monitoring. Ostrom (1990, 2009) collated cases of shared resources and discovered that the institutional arrangements in most successful cases involved a combination of public and private institutions. She summarized eight principles of successful CPR governance: clearly defined boundaries, proportional equivalence between benefits and costs, collective choice arrangements, monitoring, graduated sanctions, conflict resolution mechanisms, recognition of rights to organize, and nested firms. These eight principles are indicators of an efficient CPR system and efficient shared resource use. If a district's CPR management system adheres to these principles, the system can incentivize resource users to voluntarily comply with the system's operating rules and monitor compliance to ensure that the system is sustainable (Patel et al., 2007).

In addition to individual manufacturers, government agencies, and nearby residents, organizations are critical actors in the adaptive resilience of industrial areas. The behavior of an organization is the collective action of a group that shares common understanding of the organization's goals (Weick and Sutcliffe, 2007). The adaptive capacity and learning capability of organizations in industrial areas, including industrial organizations, disaster preparation groups, response organizations, or community organizations, can significantly affect the resilience and adaptive capacity of industrial areas. Industrial organizations include industry promotion associations and manufacturers' associations, whose members include not only manufacturers but also government representatives and local opinion leaders who participate in activities hosted by the organization or take on advisory roles. Disaster prevention and response organizations may comprise manufacturers, industrial area managers, government representatives, or civil societies. Community organizations consist of manufacturers, management units, and residents of the surrounding communities and solve common problems between the industrial area and the community.

As previously mentioned, the operation of CPRs requires collective action by the users and stakeholders of firmware resources to establish mutual trust, commitment, and supervision. To achieve effective resilient resource sharing, the CPR governance model establishes partnerships between local governments, manufacturers, communities, and related organizations.

According to the present study's literature review, adaptive resilience indicators for industrial areas should include the factors influencing the resilience of cities (UN-Habitat and DiMSUR, 2020; Ribeiro and Gonçalves, 2019); the resilience of industrial areas according to the type, frequency, and extent of disasters (Timmerman, 1981; Adger, 2000); regional infrastructure; disaster prevention and relief resources and equipment; vendor characteristics; industrial organizations (Tierney, 2007; Zhang et al., 2009; Lo et al., 2019; Chen et al., 2019); and CPRs (Ostrom, 1990, 2009). *Table 1* presents the indicators that are used for the development of this study's FDM questionnaire.

Materials and methods

Analysis of industrial area development in Taiwan

The Industrial Development Bureau, Ministry of Economic Affairs (2022) pointed that the industrial land supply in Taiwan includes industrial areas within urban planning areas and industrial land outside urban planning areas totaling approximately 47,916.82

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hectares. The total industrial land outside urban planning areas is 25,182.9 hectares, accounting for 52.56% of the total industrial land. Additionally, Taiwan has different industrial areas, such as industrial parks, science parks, technology industrial parks, and agricultural biotechnology parks, that have been established on the basis of the designated purpose of the industrial land. Industrial parks are mainly use for traditional manufacturing and are developed by either government entities or private individuals. Industrial parks are used for the electronics, semiconductor, and communications technology industries; technology industrial parks are used for the electronics, general manufacturing, and service industries; and agricultural biotechnology parks are used for industries related to agriculture and environmental technology. Most government-funded parks have management centers. However, no management center for industrial areas, including those inside and outside urban plans, has been established for the private sector. The role of the government as a development unit affects the ability of industries to adapt. Whether the governmental development units can affect resilience is one of the main focuses of this study.

Table 1. *Indicators of the resilience adjustment capability of industrial areas*

Dimension	Indicator		Measurement	References
A. Vulnerability	A1. Disaster type		Number of disasters (floods, earthquakes, and slope disasters) that occurred in industrial areas in the past 10 years	Adger (2000); Timmerman (1981); Cutter et al. (2008); Buckle et al. (2001)
	A2. Disaster frequency		Frequency of disasters in industrial areas in the past 10 years	
	A3. Potential disaster impact area		Area affected by disasters in the industrial area in the past 10 years	
B. Urban environment	B1. Land use Intensity	B1-1. Industrial area	Ratio of industrial area to total urban area	Chelleri (2012); Coaffee et al. (2018); Boyd and Juhola (2015); Ribeiro and Gonçalves (2019); UN-Habitat and DiMSUR (2020)
		B1-2. Residential and commercial area	Ratio of area of residential and commercial areas to the total urban area	
	B2. Urban Infrastructure	B2-1. Drainage facilities	Number of pumping stations in the urban area	
		B2-2. Emergency roads	Road service standards of main roads during peak hours within a 500-m radius of industrial areas	
		B2-3. Police and fire units	Location and number of police and fire units in the urban area	
		B2-4. Hospitals	Location and number of hospitals in the urban area	
		B2-5. Emergency shelter	Number of emergency shelters and number of people and amount of area that can be accommodated in the urban area	
	B3. Neighborhood Residents	B3-1. Disaster prevention awareness	Number of disaster prevention drills completed by neighborhood residents next to the industrial area	
		B3-2. Education level	Education level of people next to the industrial area	
		B3-3. Income	Income of people next to the industrial area	
C. Industrial environment	C1. Infrastructure	C1-1. Drainage facilities	Number of pumping stations in the industrial area	Tierney (2007); Zhang et al. (2009); Lo et al. (2019); Chen et al. (2019)
		C1-2. Emergency power supply	Number of generators in the industrial area	
	C2. Disaster prevention and rescue resources	C2-1. Disaster relief equipment	Number and type of disaster relief supplies in the industrial area	

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Dimension	Indicator		Measurement	References
		C2-2. Emergency Shelter	Number of emergency shelters, number of people that can be accommodated, and amount of space that can be allocated in the industrial area	
		C2-3. Emergency roads	Road service standards of main roads during peak hours in the industrial areas	
		C2-4. Police and fire units	Number of police and fire units in the industrial area	
	C3. Industrial properties	C3-1. Industry type	Industry type of all factories in the industrial area	
		C3-2. Water demand	Average water consumption (in tons) of factories over a 5-year period in the industrial area	
		C3-3. Electricity demand	Average electricity consumption (in kilowatts) of factories over a 5-year period in the industrial area	
		C3-4. Disaster prevention awareness	Number of disaster prevention drills conducted by factories and management units in the industrial area	
		C3-5. Factory numbers	Number of factories in the industrial area	
		C3-6. Factory area	Area of factories in the industrial area	
D. Factory properties	D1. Organization and scale	D1-1. Number of employees	Number of employees	Chang and Falit-Baiamonte (2002); Tierney (2007); Zolli and Healy (2012); Berrouet et al. (2018); Chen et al. (2019); Khazai et al. (2013)
		D1-2. External organization members	Number of industrial organizations and disaster prevention organizations that each manufacturer participates in	
		D1-3. Internal operation process	Standard processes for internal operations of each factory	
		D1-4. Operational adaptation	Adjustment operation methods for the operational needs of each factory	
		D1-5. External network	External network links of factories	
		D1-6. Capitalization	Capitalization of the factory	
		D1-7. Area	Land and floor area of the factory	
	D2. Factory properties	D2-1. Industry type	Industry type of each factory	
		D2-2. Operating trends	Factories' profitability and revenue growth in the past 5 years	
		D2-3. Market and product diversity	Diversity of markets and products of factories	
	D3. Employees	D3-1. Disaster prevention awareness	Number of disaster prevention drills conducted by each factory	
		D3-2. Education level	Education level of employees in each factory	
		D3-3. Age	Age of employees in each factory	
E. Governance and adaptation	E1. Management organizations		Management organizations (including service centers, industrial organizations, or disaster prevention organizations) in the industrial area	Feeny et al. (1990); Hardin (1968); Lo et al. (2019); Ostrom (1990); Ostrom (2009);
	E2. Common-pool resource governance	E2-1. Supervision	Supervision norms or mechanisms of organizations in the industrial area	

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Dimension	Indicator		Measurement	References
		E2-2. Emergency response mechanism	Plans for emergency response, reconstruction, and disaster mitigation of organizations	Rhodes (1997)
		E2-3. Discussion platform	Communication platform and mechanism of organizations	
		E2-4. Shared resources	Whether an organization has ever shared resources with other organizations	
		E2-5. Rule-making	Rules regarding shared resources of each organization	
		E2-6. Conflict resolution	Conflict resolution mechanisms for each organization	
	E3. Member diversity		Diversity of organization members (including their affiliation with the public sector or private sector, factories, and cross-industry factories and whether they are customers or neighboring residents)	

Industrial land and urban development areas are mainly concentrated in the western part of Taiwan. Because of Taiwan’s small land area and high population density, with 643 people per square kilometer at the end of 2022, it is the second most densely populated country in the world, with over 10 million people, after Bangladesh (Executive Yuan, 2023), so most of the industrial parks are concentrated in urban areas. Disasters in industrial areas seriously affect neighboring urban areas; thus, enhancing the resilience of industrial areas is crucial. The distribution of industrial land in Taiwan is illustrated in *Figure 3*.

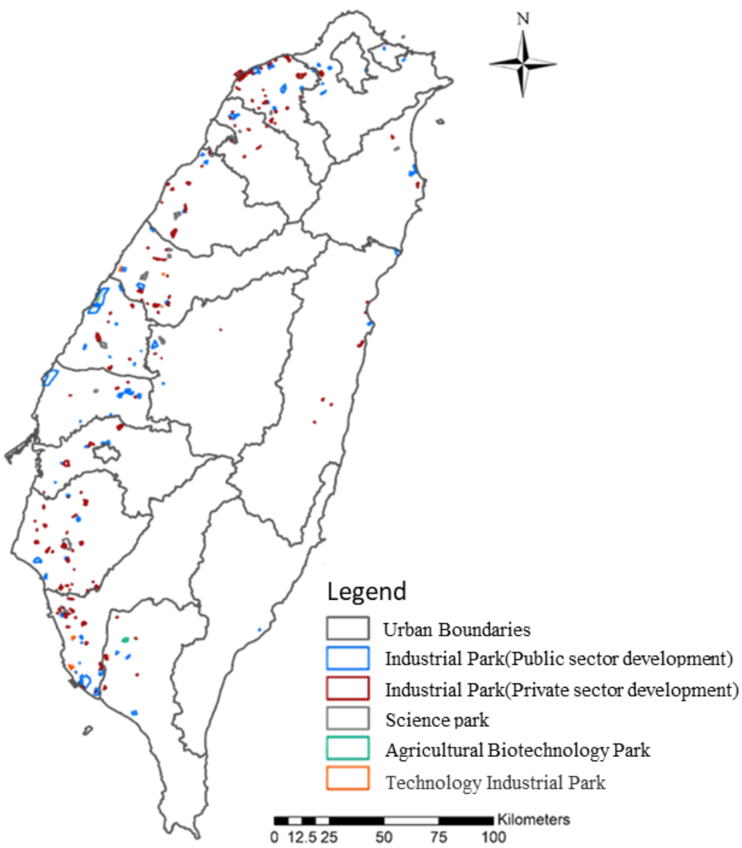

Figure 3. *Distribution of industrial land in Taiwan*

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In this section, the FDM is used to establish the components and indicators for assessing the resilience of industrial areas. Furthermore, the weight values and dynamic relationships between the components and indicators are analyzed using the DANP, and the empirical results are discussed.

Establishment of indicators for assessing the resilience of industrial areas

In this study, indicators for assessing the resilience of industrial areas are developed through the study's literature review (*Table 1*). Moreover, FDM is used to evaluate expert opinions on the structure of this study and to establish criteria for selecting indicators. The FDM uses double triangular fuzzy numbers and the gray zone testing (*Fig. 4*) to analyze and integrate expert opinions (Chen et al., 2022; Tseng et al., 2022). The FDM is more objective and reasonable than single triangular fuzzy numbers are and can reduce the required number of repeated surveys.

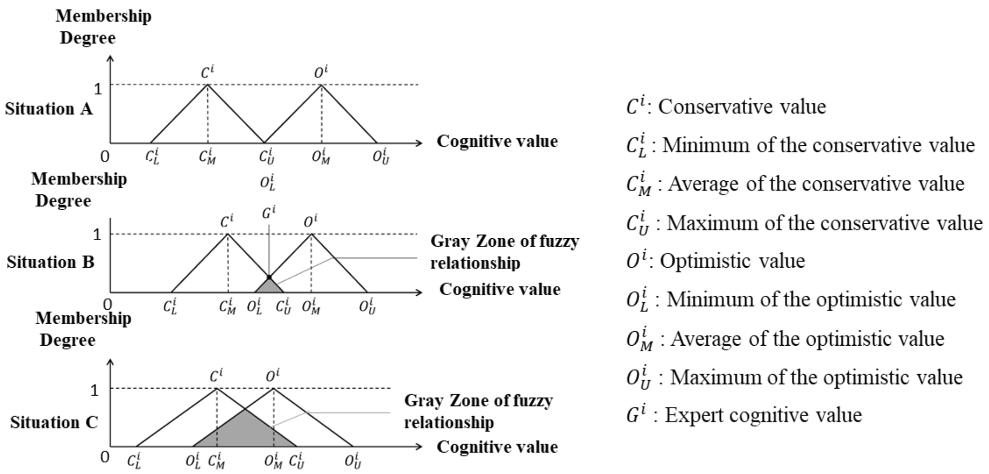

Figure 4. *Double triangular fuzzy numbers*

The gray zone testing is a method to test whether expert opinions have reached a consensus (Chen et al., 2022; Tseng et al., 2022). Situation A in *Figure 4* indicates no overlap between the two triangular ambiguities ($C_U^i \leq O_L^i$). The maximum of the experts' conservative value is less than or equal to the minimum of the experts' optimistic value, which indicates that the expert opinion values have a consensus band. Situation B indicates that the two triangular ambiguities overlap ($C_U^i > O_L^i$), and the maximum of the experts' conservative value is more significant than the minimum of the experts' optimistic value. However, the fuzzy gray area ($Z^i = C_U^i - O_L^i$) is smaller than the mean of the opinions ($M^i = O_M^i - C_M^i$), which means that although no consensus band is present between the two expert opinions, given the extreme value, the minimum of the experts' conservative value is higher than the minimum of the optimistic value. The experts' conservative and optimistic values are not sufficiently far apart from each other to cause disagreement. Situation C indicates that the two triangular fuzzy numbers overlap ($C_U^i > O_L^i$). Thus, the maximum conservative value is larger than the minimum optimistic value, and the fuzzy gray area ($Z^i = C_U^i - O_L^i$) is larger than the mean opinion ($M^i = O_M^i - C_M^i$), which indicates that expert opinions diverge too much and no consensus can be reached.

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Regarding the number of experts selected, Saaty (2005) suggested that the optimal group of experts should be 5 and not exceed 15. In the present study, 10 people with professional backgrounds or practical experience in urban planning, industrial land planning, and firmware planning are invited to answer a questionnaire survey from January to March 2022. The participants are two industry experts, three representatives of relevant government agencies, and five academics. The FDM and DANP are explained in detail in the questionnaire to ensure that the experts and scholars fully understand the questionnaire and assessment procedures and provide reasonable responses. The scree test (*Fig. 5*) is used to analyze the indicators. Tseng et al. (2022) pointed that the important criteria can be selected if the consensus values Gi are greater than a given threshold value between 6.0 and 7.0. A cognitive value (Gi) of 6.20 is set as a threshold value; a higher consensus value indicates that the indicator had higher importance and vice versa. A total of 24 indicators with a consensus value (Gi) greater than 6.20 (*Table 2*) are determined to have a positive value (Zi), and all questionnaire results reach convergence.

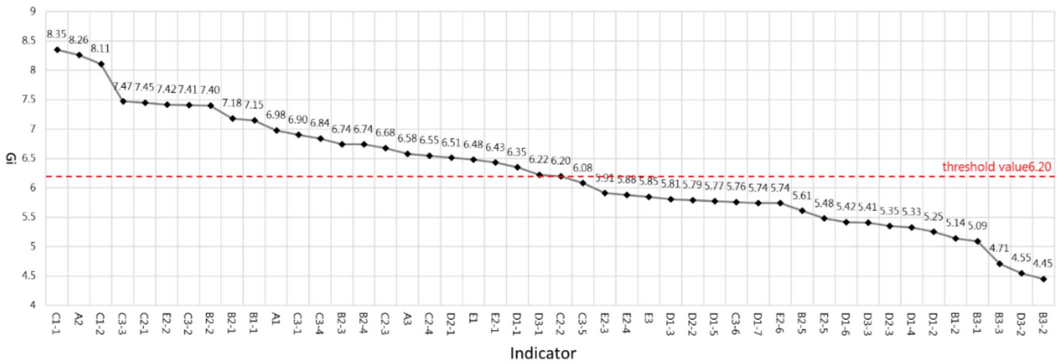

Figure 5. *Scree test of experts' cognitive values (Gi) of indicators*

The top five indicators of expert consensus are drainage facilities, disaster frequency, emergency power supply, electricity demand, and disaster relief equipment. The results of the FDM analysis indicate that the experts consider the industrial environment dimension to be the most crucial and influential component in assessing the resilience of industrial areas, followed by the frequency of disasters. The interaction and weighting of the indicators are further analyzed using the DANP to determine the critical indicators that affect the resilience of industrial areas.

Network analysis of the assessment orientation and indicators of the resilience of industrial areas

After the 24 indicators are identified using the FDM (*Table 2*), the DANP method is used to explore the relationship between the indicators and their weighting values. The DANP method is a combination of the DEMATEL and ANP, which enables construction of interrelated network models for analyzing complex real-world situations (Gabus et al., 1972). By using DEMATEL, the relationships between indicators can be identified, and the influence of each indicator can be evaluated, even if each indicator's importance is relatively low with respect to decision-making. Improving a single indicator can lead to the relevance of the overall dimension being insufficiently considered, resulting in an ineffective investment of resources. Because the indicators of

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the present study are highly correlated, the DANP can be used to demonstrate the causality and interactions among the indicators, and the DANP is more suitable for this study than the ANP method is.

Table 2. *Results of FDM analysis (Gi > 6.20)*

Dimension	**Indicator**			**Ci**		**Oi**		**Ai**		**Geometric mean**			**Zi**	**Gi**
				min	**max**	**min**	**max**	**min**	**max**	**Ci**	**Oi**	**Ai**		
A. Vulnerability	A1.		Disaster type	4	7	7	10	6	9	5.23	8.72	7.29	3.49	6.98
	A2.		Disaster frequency	3	9	8	10	7	9	5.59	9.19	7.96	2.60	8.26
	A3.		Potential disaster impact area	4	7	6	10	5	9	5.25	8.40	7.16	2.15	6.58
B. Urban environment	B1.		Industrial area	3	9	6	10	5	9	5.00	8.49	6.93	0.49	7.15
	B2. Urban infrastructure	B2-1.	Drainage facilities	4	7	7	10	6	9	5.45	8.92	7.33	3.47	7.18
		B2-2.	Disaster prevention roads	3	9	6	10	5	9	5.42	9.11	7.58	0.69	7.40
		B2-3.	Police and fire units	3	7	8	10	5	8	4.86	8.63	6.74	4.77	6.74
		B2-4.	Hospital numbers	3	7	6	10	4	8	4.60	8.10	6.26	2.50	6.74
C. Industrial environment	C1. Infrastructure	C1-1.	Drainage facilities	4	9	8	10	6	10	6.18	9.53	7.91	2.35	8.35
		C1-2.	Emergency power supply	4	8	9	10	8	10	6.46	9.77	8.42	4.31	8.11
	C2. Disaster prevention and rescue resources	C2-1.	Disaster relief equipment	4	7	8	10	7	8	5.49	9.42	7.43	4.93	7.45
		C2-2.	Emergency shelter	3	7	5	10	5	8	4.85	8.22	6.83	1.37	6.20
		C2-3.	Disaster prevention road	3	7	6	10	4	9	5.54	9.11	6.85	2.57	6.68
		C2-4.	Police and fire units	3	7	6	10	5	8	5.11	8.27	6.59	2.16	6.55
	C3. Industrial properties	C3-1.	Industry type	3	7	7	10	6	9	5.15	8.64	7.22	3.49	6.90
		C3-2.	Water demand	3	8	7	10	5	10	5.54	8.71	7.16	2.17	7.41
		C3-3.	Electricity demand	4	8	7	10	6	10	5.93	8.83	7.41	1.89	7.47
		C3-4.	Disaster prevention awareness	3	8	6	10	5	9	4.91	8.24	6.77	1.33	6.84
D. Factory properties	D1.		Number of employees	1	7	6	10	3	8	3.70	7.81	5.55	3.11	6.35
	D2.		Industry type	3	7	6	10	4	8	4.82	8.28	6.46	2.46	6.51
	D3.		Employee awareness of disaster prevention	1	8	5	10	4	9	4.00	7.73	6.09	0.73	6.22
E. Governance and adaptation	E1.		Management organization	2	7	6	10	5	8	4.63	8.22	6.53	2.59	6.48
	E2.		Supervision	2	7	6	10	5	8	3.98	8.25	6.60	3.26	6.43
	E3.		Emergency response and plan	2	8	7	10	5	9	5.27	8.94	7.39	2.67	7.42

The DANP analysis of the influence matrix yields the r_i and d_j values of the influencing constructs and indicators, where r_i is the value that indicates the amount an indicator influences other indicators and d_j is the value that indicates the amount an indicator is influenced.

$r_i + d_j$ represents the prominence, which is the total influence of the construct or indicator.

$r_i - d_j$ represents relation, which is the degree of causality between the indicators or constructs.

$r_i - d_j > 0$ represents a leading indicator and signifies that an indicator can influence other indicators.

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$r_i - d_j < 0$ represents an influenced indicator and signifies that an indicator is influenced by other indicators.

The weight is the importance of the indicator, as perceived by the experts. The results of the analysis of the influence network relationship among the indicators are discussed in Section 4.2.1.

Analysis of the influence network relationship related to the resilience of industrial areas

According to the analytical results regarding the five dimensions (*Table 3; Fig. 6*), the highest $r + d$ value (centrality) for vulnerability and for governance and adaptation is 1.478, which indicates that these two dimensions have the strongest influence on the resilience and adaptability of industrial areas. Industrial environment ($r + d = 1.445$) and factory properties ($r + d = 1.434$) also have notable influences on the resilience and adaptability of industrial areas. The $r + d$ values for these four directions are all greater than the average value of 1.43.

Table 3. *Prominence and relations of five dimensions*

Dimension	r- value	d-value	Prominence (r + d)	Relation (r-d)
A. Vulnerability	0.866	0.612	1.477	0.253
B. Urban environment	0.636	0.705	1.341	-0.069
C. Industrial environment	0.647	0.798	1.445	-0.151
D. Factory properties	0.743	0.691	1.434	0.052
E. Governance and adaptation	0.696	0.781	1.478	-0.085
Average			1.43	

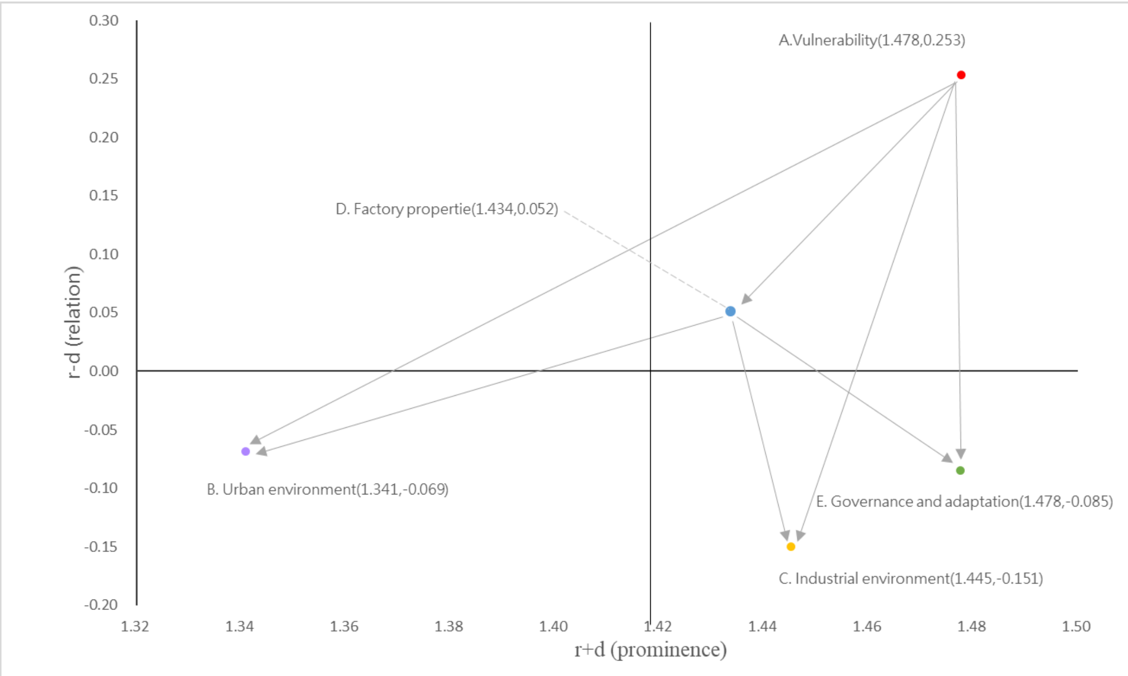

Figure 6. *Network relationship of five dimensions*

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Regarding causality, the vulnerability and factory properties dimensions has $r - d$ values greater than 0, which indicates that they are leading indicators and are the cause in the cause–effect relationship. The three dimensions of urban environment, industrial environment, and governance and adaptation have an $r - d$ value of less than 0, which indicates that they are influenced indicators and the effects of causality. As previously mentioned, although governance and adaptation is one of the most critical components of the resilience of industrial areas, indicators under this dimension must be improved through the vulnerability and factory properties dimensions.

Network relationship analysis of the indicators of the resilience of industrial areas

Each indicator's $r + d$ (centrality) and $r - d$ (causality) values are summed and divided by the number of indicators. The indicators' average $r + d$ value (centrality) is 6.82, and the average $r - d$ value (causality) is 0. The results are used as an estimate of the concentration trend of the causal matrix (*Table 4*). The causal matrix is divided into four quadrants (*Fig. 7*), as follows:

Quadrant I: $r - d > 0$ and $r + d > 6.82$, which indicates high causality and high centrality and that the indicator is a critical factor and should be prioritized for improvement. Indicators in Quadrant I are disaster type (A1), disaster frequency (A2), potential disaster impact area (A3), industrial area (B1), industry type (C3-1), and industry type (D2).

Quadrant II: $r - d > 0$ and $r + d < 6.82$, which indicates high causality and low centrality. The indicator is independent and affects other indicators when selected for improvement. This indicator is the second target for improvement. Indicators in Quadrant II are drainage facilities (B2-1) and number of employees (D1).

Quadrant III: $r - d < 0$ and $r + d < 6.82$, which indicates low causality and low centrality. These indicators are slightly effective in improving problems and are therefore not recommended for prioritization for improvement. The indicators are emergency roads (B2-2), police and fire units (B2-3), hospital numbers (B2-4), drainage facilities (C1-1), emergency shelter (C2-2), emergency roads (C2-3), police and fire units (C2-4), water demand (C3-2), electricity demand (C3-3), employee awareness of disaster prevention (D3), management organizations (E1), and supervision (E2).

Quadrant IV: $r - d < 0$ and $r + d > 6.82$, which indicates low causality and high centrality. Although the indicator is a problem that must be solved, improvements to the indicator must be achieved through a cascading effect from improvements to other indicators. Indicators in this quadrant are emergency power supply (C1-2), disaster relief equipment (C2-1), disaster prevention awareness (C3-4), and emergency response and planning (E3).

The influence network of each indicator (*Fig. 6*) reveals that the $r + d$ values (i.e., centrality) of the 10 indicators are toward the right side of the graph and larger than the average value of 6.82; thus, they have high centrality. The actual influence of these 10 indicators is relatively high. The order of the indicators from most influential to least influential is as follows: emergency response and planning (E3), industry type (C3-1), industry type (D2), potential disaster impact area (A3), industrial area (B1), disaster frequency (A2), disaster relief equipment (C2-1), emergency power supply (C1-2), disaster prevention awareness (C3-4), and disaster type (A1).

Regarding $r - d$ (i.e., causality), the indicators with values greater than 0 are disaster type (A1), disaster frequency (A2), potential disaster impact area (A3), industrial area (B1), drainage facilities (B2-1), industry type (C3-1), number of employees (D1), and

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industry type (D1). These eight indicators are leading indicators, that is, the cause in the cause–effect relationship. Indicators with values less than 0 are emergency roads (B2-2), police and fire units (B2-3), hospital numbers (B2-4), drainage facilities (C1-1), emergency power supply (C1-2), disaster relief equipment (C2-1), emergency shelter (C2-2), emergency roads (C2-3), police and fire units (C2-4), water demand (C3-2), electricity demand (C3-3), disaster prevention awareness (C3-4), employee awareness of disaster prevention (D3), management organizations (E1), supervision (E2), and emergency response and planning (E3). These indicators are considered influenced indicators, which are the effect in the cause–effect relationship. The effect of improvements to the influenced indicators on the resilience of industrial areas only occurs through improvements to the leading indicators.

Table 4. *Prominence and relations of indicators*

Dimension	Indicator			r-value	d-value	Prominence (r + d)		Relation (r-d)	
						Value	Ranking order	Value	Ranking order
A. Vulnerability	A1.	Disaster type		4.327	2.601	6.927	10	1.726	1
	A2.	Disaster frequency		4.347	2.785	7.133	6	1.562	2
	A3.	Potential disaster impact area		4.284	3.166	7.450	4	1.119	3
B. Urban environment	B1.	Industrial area		3.817	3.399	7.216	5	0.418	6
	B2. Urban Infrastructure	B2-1.	Drainage facilities	3.419	3.163	6.582	16	0.256	8
		B2-2.	Disaster prevention roads	3.316	3.379	6.695	13	-0.062	10
		B2-3.	Police and fire units	2.709	3.205	5.914	23	-0.497	18
		B2-4.	Hospital numbers	2.496	3.145	5.641	24	-0.650	21
C. Industrial environment	C1 Infrastructure	C1-1.	Drainage facilities	2.947	3.469	6.416	21	-0.523	19
		C1-2.	Emergency power supply	3.314	3.795	7.109	8	-0.480	17
	C2. Disaster prevention and rescue resources	C2-1.	Disaster relief equipment	3.132	3.980	7.111	7	-0.848	23
		C2-2.	Emergency shelter	2.874	3.904	6.778	12	-1.031	24
		C2-3.	Disaster prevention road	3.041	3.743	6.785	11	-0.702	22
		C2-4.	Police and fire units	2.950	3.537	6.488	17	-0.587	20
	C3. Industrial properties	C3-1.	Industry type	4.008	3.700	7.708	2	0.308	7
		C3-2.	Water demand	3.026	3.377	6.403	22	-0.351	15
		C3-3.	Electricity demand	3.121	3.360	6.481	19	-0.239	13
		C3-4.	Disaster prevention awareness	3.348	3.698	7.046	9	-0.350	14
D. Factory properties	D1.	Number of employees		3.591	2.894	6.485	18	0.697	5
	D2.	Industry type		4.324	3.358	7.682	3	0.965	4
	D3.	Employee awareness of disaster prevention		3.118	3.348	6.466	20	-0.230	12
E. Governance and adaptation	E1.	Management organization		3.285	3.384	6.669	14	-0.099	11
	E2.	Supervision		3.310	3.347	6.658	15	-0.037	9
	E3.	Emergency response and plan		3.706	4.073	7.779	1	-0.367	16

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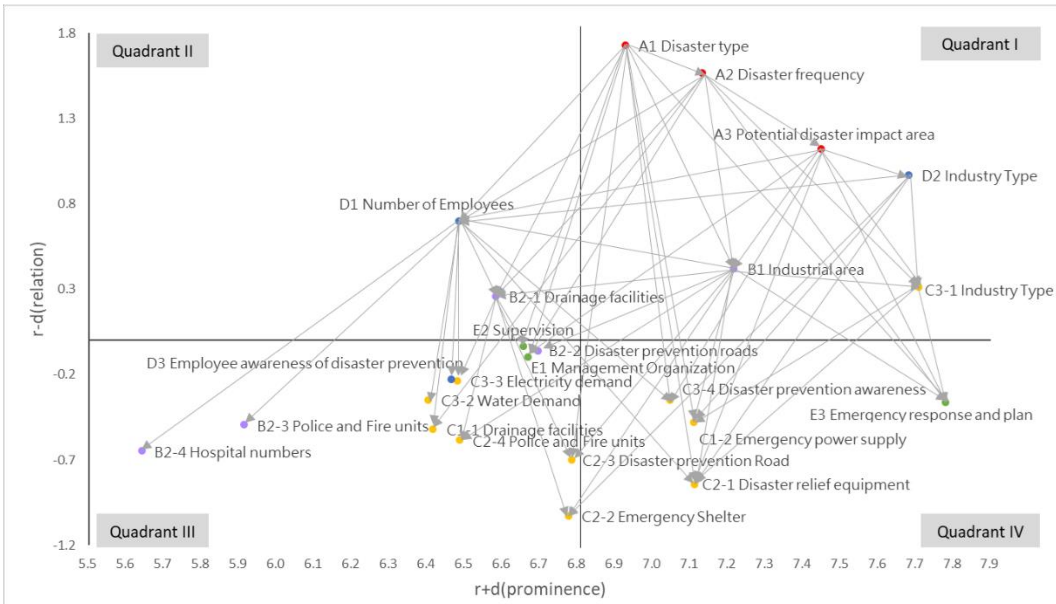

***Figure 7.** Network relationship of indicators*

To understand the effect of each indicator on the disaster resilience of industrial areas, the DANP method is used, and determine the weight values of each indicator are determined (*Table 5*). The top five indicators are emergency response and planning (E3), management organization (E1), employee awareness of disaster prevention (D3), supervision (E2), and industry type (D2). The management organization (E1), supervision (E2), and emergency response and planning (E3) indicators were all under the governance and adaptation dimension. The findings indicate that experts consider an organization's emergency response and planning to have the greatest effect on disaster resilience in industrial areas. Moreover, these results indicate that experts agree with Ostrom (1990, 2009) on the importance of shared resource management in organizations and governance for the resilience of industrial areas.

Results and discussion

Figure 8 presents the dimensions and indicator weights that affect the adaptability of industries and their rankings. The top three areas of centrality ranked from most to least influential are governance and adaptation, vulnerability, and industrial environment. In the weighting analysis, industrial environment, governance and adaptation, and urban environment are the top three weighted components. Additionally, governance and adaptation have the highest $r + d$ (i.e., centrality) value and the second highest weighting, which indicates that governance and adaptation are crucial to the resilience and adaptability of industrial areas. However, governance and adaptation features influence indicators (i.e., $r - d < 0$) that must be improved through several indicators under the vulnerability and factory properties dimensions.

The results indicating an emphasis on governance and adaptation demonstrate that the management organizations, monitoring mechanisms, and emergency response plans of industrial areas contribute to their resilience and adaptability. As mentioned previously, government-developed industrial areas in Taiwan have management centers

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that are responsible for disaster prevention and response and that interact with local governments, manufacturers, industrial organizations, and neighboring residents. Therefore, management centers may enhance the resilience and adaptability of industrial areas and be an essential indicator when the resilience of industrial areas is analyzed. To enhance the governance and adaptability of industrial areas, the government, public, and relevant organizations should jointly manage shared resilience resources by establishing a shared resource management organization, a monitoring mechanism, and disaster prevention and response plans. Such measures can reduce the cost of government administration and streamline resource use (Feeny et al., 1990; Dixit et al., 2009). Thus, a CPR governance model is essential for assessing the adaptive resilience of industrial areas.

Table 5. *Indicator weight values*

Dimension	Indicator			Weight Value	Ranking order
A. Vulnerability	A1.		Disaster type	0.05211	9
	A2.		Disaster frequency	0.05574	8
	A3.		Potential disaster impact area	0.06352	6
B. Urban environment	B1.		Industrial area	0.04079	10
	B2. Urban infrastructure	B2-1.	Drainage facilities	0.03805	13
		B2-2.	Disaster prevention roads	0.04064	11
		B2-3.	Police and fire units	0.03847	12
		B2-4.	Hospital numbers	0.03778	14
C. Industrial environment	C1. Infrastructure	C1-1.	Drainage facilities	0.02096	22
		C1-2.	Emergency power supply	0.02294	17
	C2. Disaster prevention and rescue resources	C2-1.	Disaster relief equipment	0.02409	15
		C2-2.	Emergency shelter	0.0237	16
		C2-3.	Disaster prevention road	0.02275	18
		C2-4.	Police and fire units	0.02146	21
	C3. Industrial properties	C3-1.	Industry type	0.02238	20
		C3-2.	Water demand	0.02048	23
		C3-3.	Electricity demand	0.02039	24
		C3-4.	Disaster prevention awareness	0.02274	19
D. Factory properties	D1.		Number of employees	0.05813	7
	D2.		Industry type	0.06738	5
	D3.		Employee awareness of disaster prevention	0.0678	3
E. Governance and adaptation	E1.		Management organization	0.06832	2
	E2.		Supervision	0.06772	4
	E3.		Emergency response and plan	0.08166	1

Dimension A is the second most crucial dimension affecting resilience but has the lowest weighting of the five dimensions. Experts may believe that the frequency of disasters decreases with the number of types of disasters and that the resilience of an industrial area increases as the size of the area of impact decreases. The occurrence and frequency of natural disasters (e.g., earthquakes and typhoons) cannot be reduced

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through prevention. Consequently, Dimension A has the lowest weight. However, the frequency and impact of fires, which are common in industrial areas, can be reduced by local governments, industrial area management units, and manufacturers through the proper management and maintenance of equipment, the proper management of environments, and the establishment of standard operating procedures (Tierney, 2007; Zhang, 2009; Lo et al., 2019; Chen et al., 2019). For natural hazards, a disaster prevention database can be established to predict the potential effects of disasters through historical data to facilitate disaster avoidance planning and the provision of material needs. The leading category is vulnerability, which, once improved, can improve the resilience of industrial areas. The indicators under the industrial environment and governance and adaptation dimensions can also be enhanced; therefore, they should be prioritized.

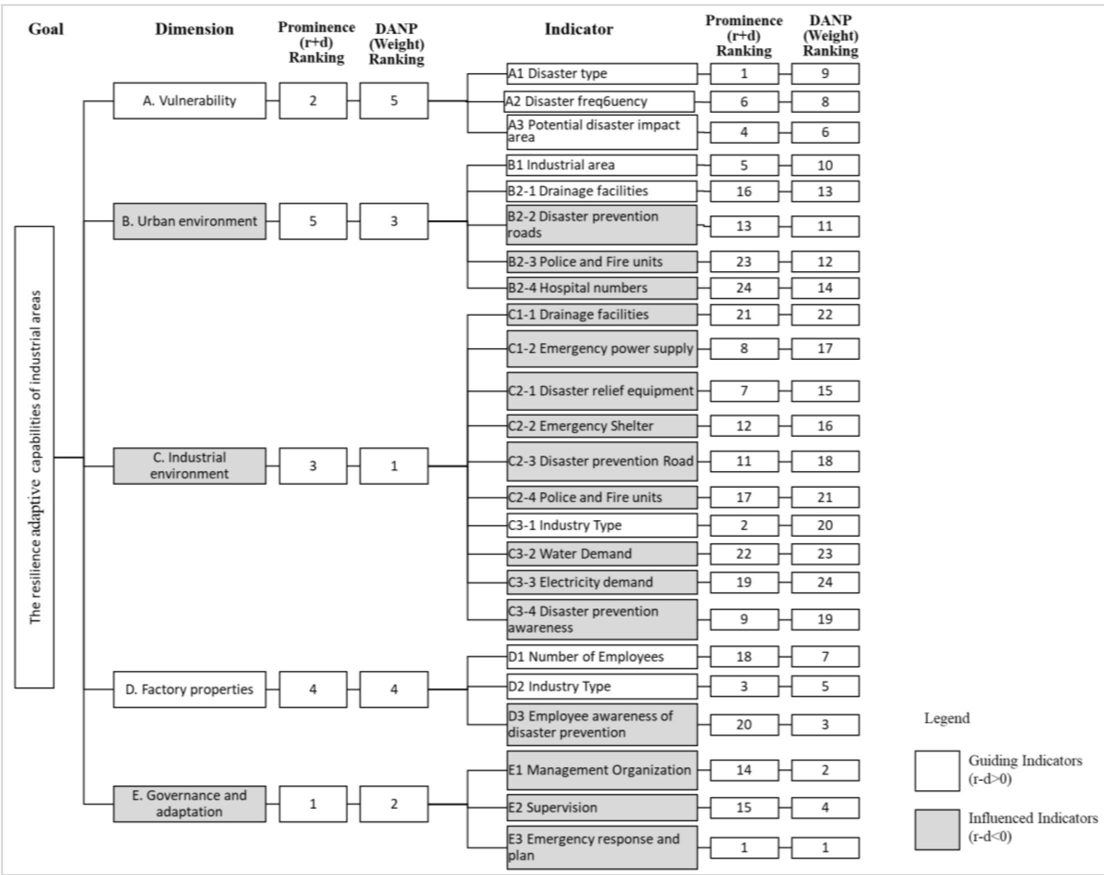

Figure 8. *Ranking of dimensions and indicators of adaptive resilience of industrial areas*

The assessment and improvement of the resilience of industrial areas must be based on indicators to ensure improvement strategies specific to each industrial area are proposed. As presented in *Table 4* and *Figures 6* and *7*, the five indicators with the highest weights were emergency response and planning (E3), management organizations (E1), employee awareness of disaster prevention (D3), supervision (E2), and industry type (D1). E1, E2, and E3 are indicators under the governance and adaptation dimension, and D1 and D3 are indicators under the factory properties dimension. E1, E2, and E3 are ranked second, fourth, and first in the weighting,

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respectively, indicating the importance of governance and adaptability to the resilience of industrial areas. As suggested by Ostrom (1990, 2009), the eight principles of successful CPR governance involve developing an adaptation strategy and establishing a resilient shared resource management organization, monitoring mechanism, and shared resilience adaptation plan. The members of a resilience organization should be public and private sector actors, such as government agencies, manufacturers, management centers, industrial organizations, disaster prevention groups, response organizations, and community organizations. Only through cooperation and networking can CPRs be effectively used and the CPR system be maintained (Patel et al., 2007).

D3 is the third highest ranked indicator; thus, experts and scholars believe that in addition to establishing resilient and adaptive organizations in industrial areas, strengthening disaster prevention awareness among the employees of manufacturers is necessary to ensure the effective use of disaster response resources. Regarding adaptation strategies, local governments, management centers, manufacturers, and relevant disaster prevention organizations should organize regular disaster prevention training sessions or drills and establish a shared database for disaster information. Employees should also be encouraged to participate in disaster prevention training to increase disaster prevention awareness and familiarize themselves with disaster prevention tools to enhance their ability to respond to and learn from disasters. The type of industry is also a key indicator; the more hazardous the industry is, the more resilient it must be. Therefore, industrial parks should adopt different adaptation strategies on the basis of the industrial sector they are associated with.

The indicators ranked sixth through twelfth in the weighting are potential disaster impact area, number of employees, disaster frequency, disaster type, industrial area, emergency roads, and police and fire units. Potential disaster impact area, disaster frequency, and disaster type belong to the vulnerability category. Therefore, the resilience of industrial areas can be improved by identifying the disaster types and reducing the scope and frequency of artificial hazards (e.g., fires) by identifying the source of vulnerability and analyzing related governance and adaptation efforts. Number of employees is a measure of the number of employees that may be affected by a disaster and affected the indicator D3, or employee awareness of disaster prevention. To improve the resilience and adaptability of industrial areas, regular education and training sessions should be organized to enhance employees’ awareness and knowledge of disaster prevention and their ability to respond to disasters. Industrial area, emergency roads, and police and fire units are indicators of urban resilience. The larger an industrial area is, the greater the number of industries, manufacturers, factory space, and employees are needed in the area, and the greater the ripple effect of a disaster is on the city. Emergency roads in urban areas are essential for evacuating industrial areas, and whether police and firefighting units are available to support disaster response in industrial areas is critical in assessing the resilience of industrial areas. Regarding adaptation strategies, local governments should conduct an inventory of the shelters, police and fire stations, and medical institutions in their city and integrate intelligent communication facilities to improve emergency response.

Overall, assessments of the resilience of industrial areas must not only account for the weights of indicators but also the interactions between them. For influenced indicators, improving leading indicators can have a multiplier effect on the resilience

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and adaptability of an industrial area. These results are consistent with those of Miller et al. (2010); Turner (2010) and Turner et al. (2003), who suggested that adaptive resilience is influenced by the interactions between the urban environment, natural hazards, social environment, and actor–network relationships.

Conclusion

This study adopts the perspective of urban resilience, industrial area resilience, and CPR and determines the dimensions influencing the resilience of industrial areas be vulnerability, urban environment, industrial environment, factory properties, and governance and adaptation (see *Table 1*). First, after the FDM analysis, the indicators that did not reach the screening thresholds were removed. Thereafter, five dimensions remained, totaling 24 indicators. The DEMATEL analysis was then conducted to understand the interactions between the dimensions and indicators, and the DANP analysis was performed to obtain the weight of each indicator (*Fig. 7*). The results of this study are in accordance with the research context, purpose, implications, and contributions described in the introduction.

The dynamic relationships between the dimensions are first analyzed using DEMATEL. Vulnerability and factory properties are the leading dimensions, whereas governance and adaptation, urban environment, and industrial environment are the influenced dimensions. Regarding centrality, governance and adaptation has the highest value, indicating that it has the greatest influence on the resilience of industrial areas, followed by vulnerability. However, because governance and adaptation is an influenced dimension, its effect on the resilience of industrial areas is affected by the vulnerability and factory properties dimensions. By improving the leading dimensions, the effects of governance and adaptation, urban environment, and industrial environment on the resilience of industrial areas can be enhanced. These results validate the interactions between urban resilience, industrial resilience, and CPR.

According to the results of the DANP analysis, industrial environment has the highest weighting, which indicates that the physical infrastructure, disaster prevention and relief resources, and disaster prevention awareness considerably affect the resilience and adaptability of industrial areas. The dimension with the second highest weighting, governance and adaptation, is the most influential dimension in the centrality assessment. Therefore, governance and adaptation is crucial for assessing the resilience and adaptability of industrial areas. The analytical results indicate that industrial areas with a resilient shared resource adaptation organization, monitoring system, and emergency response plan have a high adaptative capacity. Moreover, the results indicate that experts believe managing adaptive resilience resources in industrial areas through government, the public, or related organizations is feasible (Feeny et al., 1990; Dixit et al., 2009). The results also verify the importance of Ostrom’s (2009) CPR governance model for the assessment of resilience adaptation in industrial areas.

Regarding the indicator analytical results, the five indicators with the highest weights are emergency response and planning (E3), management organizations (E1), employee awareness of disaster prevention (D3), supervision (E2), and industry type (D2), which demonstrates the importance of governance and adaptation. These results indicate that experts believe cooperation, consultation, supervision, disaster prevention, relief plans, and the characteristics and awareness of enterprises are key factors for assessing the resilience of industrial areas. Of these indicators, D3, E1, E2, and E3 are influenced

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indicators that must be improved through improvements to leading indicators, which can then improve the resilience and adaptability of industrial areas.

This study further proposes an adaptive resilience strategy. Regarding the vulnerability dimension, a disaster prevention database can be established to collect information on disasters and related contingency measures and reduce the occurrence of artificial disasters. To improve the urban environment dimension, disaster prevention and relief agencies must be established and linked to various urban institutions, such as police and fire services and medical institutions. In addition, intelligent communication can enhance the efficiency of ambulance services. The industrial environment dimension can be improved by strengthening infrastructure (e.g., water, electricity, and roads for disaster relief) and providing disaster prevention and relief equipment and by implementing disaster prevention drills to enhance the disaster prevention knowledge of manufacturers, employees, and management organizations. To improve factory properties, manufacturers should improve their staff's knowledge of disaster prevention and response capabilities according to their industry type. Finally, the governance and adaptation indicator is essential for resilience and adaptability. When developing adaptive resilience strategies, the eight principles of successful CPR governance (Ostrom, 1990, 2009) should be referenced. A typical resource management organization with public and private sector participation can also be established through mutual monitoring, compliance with the norms of adaptive resilience, and stable cooperation. Consequently, resilience resources can be effectively used by cities, industrial areas, and manufacturers.

This study develops a set of indicators and adaptation strategies that can serve as a reference for industrial authorities and manufacturers for assessing their adaptive resilience capabilities and improving related strategies. The results can be adapted to the specific characteristics of an industrial area to improve resilience.

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