Dynamic Resilience in Urban Road Systems: Developing a Comprehensive Assessment Framework Using Bayesian Networks

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1. Introduction

As critical infrastructure, Urban Road Systems (URS) are essential for facilitating urban flows of people, goods, and services. These systems are becoming increasingly complex and vulnerable to disruptions, significantly impacting urban traffic and socio-economic activities (Yin et al., 2023). For example, the 2011 earthquake in northeastern Japan resulted in about \$360 billion in damages and affected thousands of roadways and bridges. In such rapidly evolving environments, resilience—initially defined by Holling (1973) as the ability to resist, absorb, and recover from disturbances—is crucial for system safety and sustainability.

Research on enhancing transportation system resilience focuses on modelling, assessing, and optimizing resilience. Effective assessment methods are critical (Wang & Yuen, 2022), yet the absence of a universally accepted resilience definition complicates this (Wang et al., 2023a). Direct measurement of URS resilience is impractical due to the complexity and interconnectivity of these systems. Typically, resilience is assessed using proxy variables and Bayesian networks (BN) to model causal relationships and explore system dynamics (Wang et al., 2023b).

Given the lack of an appropriate resilience definition and the complexity of URS, this study aims to propose a comprehensive resilience assessment framework incorporating a Dynamic Bayesian Network (DBN) model for URS assessment. Initially, we propose a new definition of system resilience: "the dynamic capability of a system to withstand disturbances, characterized by the system's preparedness before disturbances, response during disturbances, and learning from the process." To capture the dynamic nature of URS and explore the system's potential learning capabilities, a DBN is employed as the assessment model. Case studies from four major Chinese cities inform recommendations for enhancing URS'S resilience.

2. Research methodology

In our research, we initially developed a static BN model inspired by Tang et al. (2020), which organizes the model into three distinct layers: Function, Quality, and Factor, aligning with a 'macro-meso-micro' framework as depicted in Fig.1. Within the Function layer, preparation and response are emphasized based on the provided definition, with six distinct capabilities identified through a comprehensive literature review. The Factor layer incorporates a diverse set of leading indicators across four dimensions—organizational, environmental, social, and technological—to assess various capabilities of resilience.

Subsequently, we advance our model by integrating a DBN that incorporates a learning capability, effectively bridging static BN models across different temporal stages. This addition presupposes that URS adapt and evolve after previous disruptions, embodying a form of experiential learning that becomes evident in subsequent challenges. In the model, the learning capability, emerging from the response activities, influences both preparation and response in future instances.

In the DBN framework, we categorize all variables as Boolean, labelled 'R' for resilient and 'NR' for non-resilient, to streamline the analysis. To generate prior probability values for variables in the factor layer, a range of sources including governmental reports and statistical yearbooks spanning 2010 to 2021 are collected. Furthermore, expert insights are leveraged to define conditional probabilities and function parameters within the model.

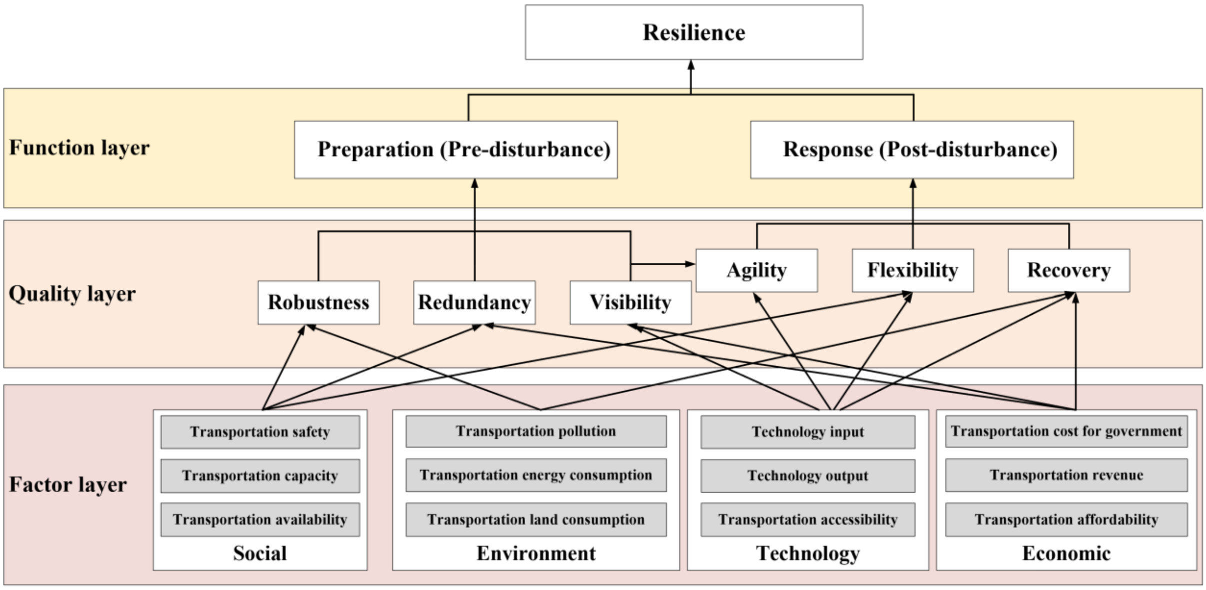

Figure 1. The structure of the proposed static BN model.

3. Results

For our study, we focused on four directly governed cities in China—Beijing, Tianjin, Shanghai, and Chongqing—as our research subjects. Utilizing the DBN frameworks previously outlined, we tailored DBN models specific to each of these municipalities. To ascertain the latent learning capability of each city's URS, we employed forward inference techniques. By setting the resilience status (Resilient = true) as evidence within the DBN, we derived the marginal posterior probabilities for learning capabilities.

Initial probabilities for learning abilities were set at 0.1, and subsequent analysis was graphically represented in Fig.2. This figure illustrates the year-on-year cumulative probability of each city's learning capability being active. The analysis revealed a consistent upward trajectory in learning capabilities across all cities, which mirrored improvements in their resilience levels. Moreover, the comparative analysis of learning capabilities among these cities reflected their relative rankings in terms of average resilience, underscoring a significant positive correlation between the systems' learning capabilities and their resilience against disruptions.

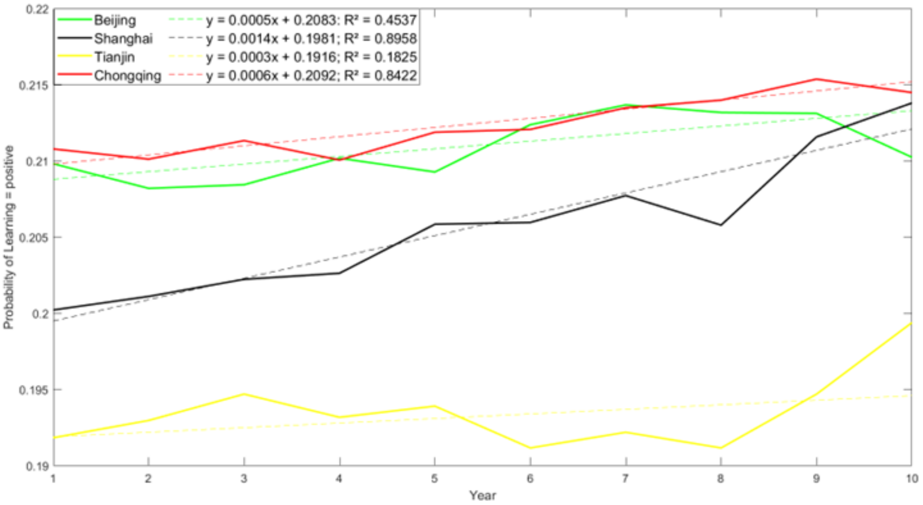

Figure 2. The probability of learning ability of urban road system in DBN model.

4. Discussion and conclusions

The primary contributions of our research are summarized as follows: 1) we introduce a novel definition of system resilience, which serves as the foundation for developing a new multi-dimensional dynamic resilience assessment framework utilizing DBN. 2) a comprehensive model facilitates a holistic resilience evaluation of URS is provided by incorporating critical factors from four key areas: economic, environmental, social, and technological. According to the case analysis, the learning ability of the system is positively related to the overall flexibility. In the future, more suggestions can be provided to decision makers through various analyses.

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