Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2023 Volume 29 Issue 6: 561–576
https://doi.org/10.3846/jcem.2023.19565

CARBON IMPACT ASSESSMENT OF BRIDGE CONSTRUCTION BASED ON RESILIENCE THEORY

Zhi Wu ZHOU*, Julián ALCALÀ, Víctor YEPES

ICITECH, Department of Construction Engineering, Universitat Politècnica de València, 46022 Valencia, Spain

Received 2 February 2022; accepted 10 July 2023

Abstract. The construction and management of large-scale projects have the characteristics of complexity, dynamic and offline, and how to evaluate it is a research problem accurately. This study addresses this question through multidisciplinary cross-applied research. The research analyses and optimizes the environmental impact of the construction stage of super-large bridges by establishing a theoretical model system of environmental impact resilience. The analysis shows that industrialized construction can save 56.31% of materials compared with traditional construction but increase the consumption of machinery and personnel by 11.18%. Ultimately, environmental pollution can be significantly reduced. This study breaks through the difficulty of accurately evaluating discrete dynamic factors. It has realized the application of multidisciplinary research to solve management optimization and design problems in the elastic and dynamic changes of super-large bridges during construction. This research provides rich theoretical models and advanced analytics experience data for environmental resilience impacts and project resilience management models, laying a solid scientific foundation for dynamic control and sustainable development assessment of statically indeterminate structures in the future.

Keywords: project management, energy, material, industrialized, environment, response.

Introduction

Since the Global Carbon Project (GCP) was established in 2001: the global carbon cycle, the impact of climate and human activities, the carbon cycle, and sustainable development have been increasingly studied (Le Quéré et al., 2014). The Intergovernmental Panel on climate change predicts that global carbon emissions will be reduced by 42–57% by 2050 and 73–107% by 2100 with effective and radical decarbonization measures. By 2045, it is estimated that net-zero greenhouse gas (GHG) emissions will be achieved (Bataille et al., 2016). Narrowing the range of the carbon cycle is of great importance to reduce the energy consumption and carbon emissions of the industry, especially for the carbon emission concentration area (King et al., 2015; Schimel et al., 2001).

Worldwide, the total energy consumption in 2018 was 13,864 Mtoe (million tonnes (t) of oil equivalent), among which the construction industry accounts for 40% (Ruparathna et al., 2016). The data from the Climate Change Committee reveals that by 2060, 230 billion m^2 of new buildings will emerge in the world. In the next 40 years (from 2018), 415 Gt of CO_2 (Carbon dioxide) will be emitted, rising to 55% of the total global emissions (Helmers et al., 2021; Penadés-Plà et al., 2018). After experiencing many challenges and obstacles, the construction industry should integrate innovative technologies into practice, breaking through critical social and technological factors (Zhang et al., 2016). The construction industry should combine green building, sustainability, and resilience theories to reduce the carbon footprint of new buildings while resisting extreme climate change. Therefore, the authors investigated and worked (refer to Section 1). The development of new industrialization has become the mainstream model of the construction industry (Yang & Cheng, 2020).

The complexity and resilience of the construction industry are affected by multiple attributes, forming a tightly coupled system featuring diversity, variability, and nonlinearity (Nemeth & Herrera, 2015). Usually, previous research focuses resilience and sustainability from the perspective of the building environment's response to natural and anthropogenic disasters. Response can be deemed as human perception and awareness of the domain (Vincenzi et al., 2018; Carpio et al., 2021). The causes and mechanisms affecting the sustainability of the resilience environ-

*Corresponding author. E-mail: *zhizh2@doctor.upv.es*

ment are shown in this study (see the Section 3 analysis); however, there is scarcely any application of resilience engineering, oriented by systematic research, which is almost zero (Yang et al., 2019) (refer to Section 1).

The problems to be solved in this study are as follows: analysing the construction and installation process of complex bridges based on resilience theory; achieving the environmental pollution control objectives for sustainable development through dynamic design evaluation. The solutions reflect the research significance of this study and prove the best combination model of green buildings (Wuni et al., 2019), sustainable development, and resilience theory (Fu et al., 2020), which lays a theoretical and practical foundation for the further study of resilience theory and its application in civil engineering.

This study establishes an environmental resilience analysis model based on resilience theory. The model is used to study the range and value of the ecological resilience influence of the bridge structure during the construction period. The numerical change process of the resilience factor is used to present the influence process of each element on the environment, thus reducing bridge environmental pollution.

The innovation lies in applying solid mechanics theory to bridges' environmental impact analysis process. The authors hope that the concepts of "resilience theory" will be understood by researchers focusing on "environmental analysis". The dynamic changes of environmental impacts are displayed in numbers and graphics so that researchers (especially "non-bridge construction experts" researchers) can figure out the ecological impact changes during the bridge construction period. In additioJn, the environmental resilience influence curve graph is drawn and defined, and the modeling theory is digitized and graphed.

The rest of this study will be divided into the following sections: Section 1. Literature review, which analyses the status of global related research; Section 2. Methodology establishes project construction management; environmental impact; resilience theory model; Section 3. Results and discussion, which is connected to case analysis; Section 4. Comparative design redesigns the original project management plan and resilience response to changes; Last Section. Conclusions, present research limitations, and future directions.

1. Literature review

Based on the literature survey of the research results proposed in Section 1, the research team determined that the Scopus database and Cite space software were used to conduct clustering network map analysis (Chen, 2017; Ge et al., 2020). The final search keywords are building, sustainability and resilience. Finally, 1307 articles (1986–2021) were retrieved.

In the keywords of the clustering network map, Modularity $Q = 0.5252 > 0.5$; Harmonic mean $(Q, S) = 0.6234 > 0.5$; Silhouette $S = 0.7668 > 0.5$. The three parameters indicate that the coupling conclusion of this literature is highly credible, and the conclusion is convincing. Clustering analysis process: the top ten central and emergent keywords after cluster analysis are (according to the analysis of the log-likelihood ratio pick-up algorithm model): resultant energy (521.39) ~ resilience framework (281.57) ~ disaster resilience (264.93) ~ geospatial assessment (256.34) ~ biological hazard (208.68) ~ natural disaster (201.56) ~ building livelihood resilience (189.45) ~ community resilience (176.03) ~ coral-associated bacterial communities (184.8) ~ workshop summary (171.62). The above keyword network cluster analysis (n = 658 cluster nodes; E = 2848 critical paths) concluded that no direct correlations to sustainability and resilience were found in the core content of articles published over thirty-six years around the world (see Figure 1a).

In the analysis of Figure 1a, 12 groups of clustered average contour value data are simultaneously obtained (the data feeds back the time area and contour value that are closest to the structure of the search keywords) – selecting the two groups of the database. $S_1 = 0.934$, the corre-

a) b)

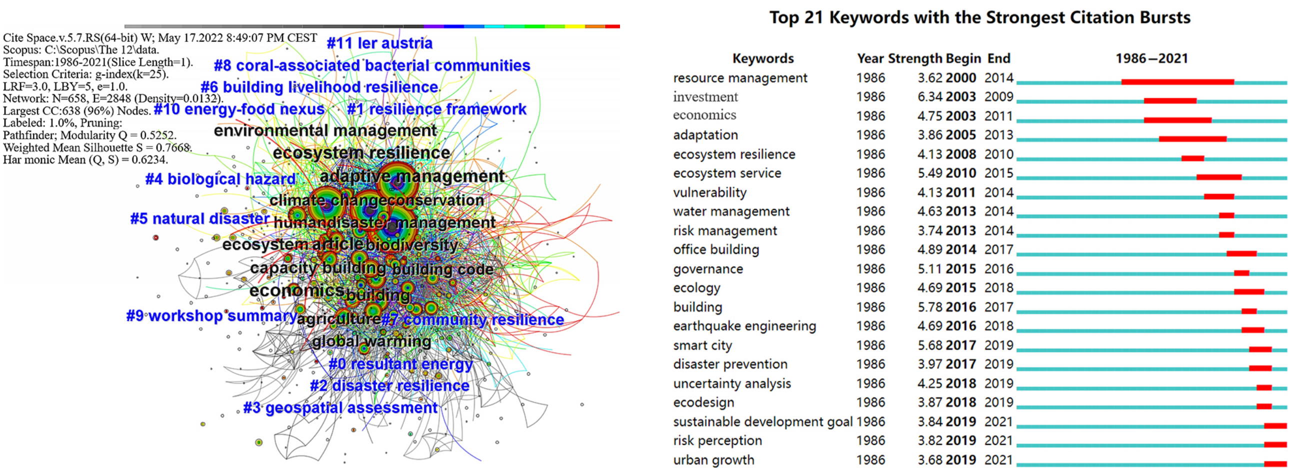

Figure 1. Algorithm program analysis: a – Analysis of keyword clustering network map; b – Analysis of the keyword strongest citation burst

sponding data are building resilience, energy-food nexus, water energy food nexus, watershed context, ecosystem management, ocean regionalization, post-modern dilemma, and regional approach. $S_2 = 0.926$. The corresponding data are ecological resilience, alpine valley, organic farming; modeling socio-ecological tourism-based system; Italian practice; risk management; Hyogo framework, and social resilience. The analysis of the two data groups shows that the time interval of the research results closest to this paper is 2002 and 2005.

The research hotspot analysis uses the weighting algorithm and the mutual information algorithm to cluster and analyze the co-citation times of the keywords and select the hotspots for research in a period. Through the analysis, 21 groups of research hotspots were obtained, and the first five groups were: resource management (2000–2014 year) ~ economics (2003–2011) ~ adaptation (2005–2013) ~ investment (2003–2009) ~ ecosystem service (2010–2015). The 21 groups of research hotspots do not duplicate the research content of this manuscript. From the changes in research hotspots, it can be found that the research field is gradually widening and moving towards the direction of sustainable development (for example, the sustainable development goal of 2019–2021), so the research in this manuscript is of great significance (Figure 1b).

Conclusion: Through the three times cluster analysis of articles published in 36 years, it can be found that the number of articles related to keywords, the number of co-citations, and the density of documents are all decreasing. The research direction of this study is even more lacking, which can fill the gap in this field and strengthen the more prosperous sustainable development research methods in the field of bridges.

2. Methodology

Resilience was initially defined as the capability of the ecosystem to absorb and rebound to external shocks. Subsequently, research deepened the resilience theory and applied it to the social ecosystem by decomposing it into two parts. The first part is the inherent resistance, namely the essential substitute response after the damage to the natural economy. Affected by uncertain factors in the environmental impact analysis, specific responses and changes in ecological resilience are caused accordingly (Xu et al., 2019). In the millennium ecosystem assessment, the concept of response is more precisely defined: it refers to the entire range of human behaviours to solve specific problems, needs, opportunities, or problems, including policies, strategies, and interventions. In natural ecological management systems or ecosystem service systems, the response is legal, technical, institutional, economic, or behavioural, and they are affected by local, micro, regional, national, or international actions. The response ensures natural ecosystems and biodiversity, improves ecosystem services, and enhances human well-being (Srivastava et al., 2021).

Theoretical model: the theoretical model is established based on research and analysis; currently, the overall evaluation modeling for new bridge construction includes: modeling application of resilience, modeling of environmental impact, modeling of bridge construction, environmental impact of bridge materials (Yadav et al., 2020). We have combined these methods to create our theoretical model.

2.1. Modeling application theory of resilience

The analysis of relevant research literature reveals that natural and human responses face challenges globally, not just sustainable development issues. It is challenging to evaluate the effectiveness of responses and take appropriate countermeasures, such as the cognition of system and law, economy and incentives, society and behaviour, and technology and knowledge in international conventions. Human responses are not narrowly understood as different and isolated response options (actions, practices, and tools) that directly address the driving factors and proximate causes of affected resources and environmental degradation, which involve five types of activities: development, prevention, adaptation, mitigation, and repair/recovery (Briassoulis, 2017). The authors only discussed the resilience response changes of influencing factors related to the construction and installation stage in this study.

Resilience, one of adaptive resilience, can supplement changes and reduce harm to quickly implement the relevant policies (Figure 2a). Zhou et al. (2020a) studied the environmental impacts of cable-stayed bridges in four stages. The authors analysed the relationship between environmental impacts and resilience changes in bridge construction (Figure 2b).

In advanced mathematics, typical resilience index is defined as (Cimellaro et al., 2010):

$$R = \frac{\int_{t_1}^{t_L} Q(t)\,dt}{T_R}, \tag{1}$$

R is resilience index; t_1, t_L are time changes value (day).

The relationship between environmental impact and the resilience index of each stage is established as follows, and the area of the triangle represents the environmental impact value (Figure 2b):

$$R_E = \frac{\sum_{t_1}^{t_s}\left[E_{T1}\left(t_1,t_2\right)d_t+,\cdots,+E_{Ts}\left(t_{s-1},t_s\right)d_t\right]}{T_{R_E}}, \tag{2}$$

E_{T1} is change rate value of environmental impact within the range of (t_1, t_2) (%); while E_{Ts} is change rate value of environmental impact within the range of (t_{s-1}, t_s) (%).

2.2. Modeling of environmental impact

Globally, Life cycle assessment (LCA) is one of the most dynamic departments, which can assess the environment comprehensively and systematically. It has been widely included in the ranks of sustainable survey methods. In August 1990, SETAC (Society of Environmental Toxicology and Chemistry) and ISO (International Standard Organisation) jointly implemented the LCA standard.

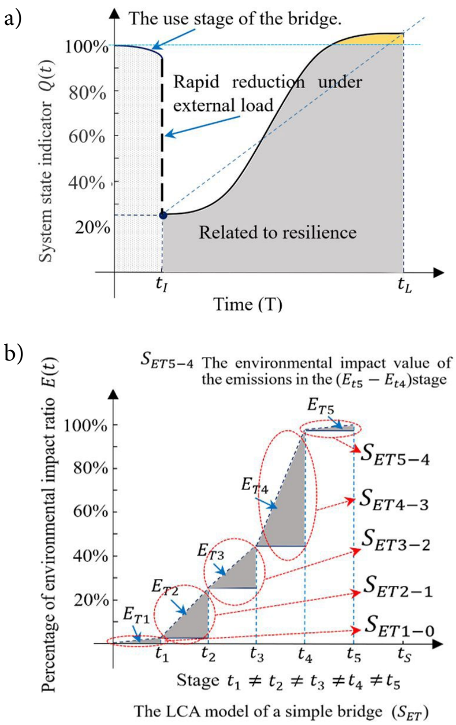

Figure 2. Research model: a – Resilience change of bridge under external load impact (Bonstrom & Corotis, 2016); b – Changes in environmental resilience at each stage of the bridge life cycle (Zhou et al., 2020a)

They revised the structural framework into four parts: target definition and scope – inventory analysis – impact evaluation – improvement evaluation. Subsequently, the LCA series of measures (ISO 14040-43) were released, revised, and condensed into two criteria, namely 14040 and 14044, in 2006. As required in the ISO framework standard, the research steps shall be divided into four stages (Finkbeiner et al., 2006).

Goal and scope: Tie Luo Ping Bridge is taken as an example. The content of the bridge LCA assessment is divided into five stages: survey and design, material manufacturing, construction and installation, maintenance and operation, and dismantling and recycling. Since the bridge's cross-section is a variable cross-section, the functional unit of the inventory data is based on 1 kg, and all relevant data is input according to the calculated information (García-Segura et al., 2018).

Definition and division of external impact: the external environmental impact factors are mainly based on stakeholders and institutional theories to analyse the factors that affect sustainable development strategies, such as government policies, partner competition et al., as well as economic, social, technological, and environmental factors, etc. (Kunc, 2018).

This study mainly studies changes in environmental resilience under the traditional building process and the industrialized installation at the bridge construction stage. The focus is on the resilient numerical evaluation of building natural resources, energy consumption, and optimization factors in a dynamic environment.

Build an environmental impact model for the construction phase:

$$\begin{cases} E_n = \sum_{T=\text{Start}}^{T=\text{Completed}} C_e\left(\lambda_{\text{Traditional}}, \lambda_{\text{Industrialization}}\right) \times \left(1 \pm \varphi_{\text{Resilience}}\%\right) \\ \lambda_{\text{Traditional}\to} \min_T F_{\text{Impact}}, 0 < F_{\text{Impact}} < 1 \\ \lambda_{\text{Industrialization}\to} \min_I F_{\text{Impact}}, 0 < F_{\text{Impact}} < 1 \end{cases}, \quad (3)$$

E_n is environmental impact data (kg); $C_e(\lambda_{\text{Traditional}}, \lambda_{\text{Industrialization}})$ is environmental impacts of different construction methods; $\varphi_{\text{Resilience}}\%$ is resilience influence Coefficient; $\min_T F_{\text{Impact}}$ is the efficiency of the combined influencing factors is minimized.

Impact factors: according to EU Product Environmental Footprint (EUPEF) standards (Jiang et al., 2020). Among them, five categories fall within key objectives of bridge LCA research: GWP (Global Warming Potential), AP (Acidification Potential), FEP (Free-water Eutrophication Potential), PMFP (Particulate Matter Formation Potential, Fume and Dust), and WP (Waste Potential).

Assessment method: the LCA assessment methods have a midpoint and an endpoint. Compare the advantages and disadvantages of the two modeling techniques, it is most appropriate to use midpoint modeling for each stage of the study and use endpoint modeling for intervals (Zhou et al., 2020a).

During the research, OpenLCA1.10.1 was used as the assessment software system; Ecoinvent, design drawings, and related national codes and standards for bridge design were used as the databases. Zhou et al. (2020a) studied the environmental impact of the cable-stayed bridge and analysed the four-stage impact factors. It is found that the construction period is more dynamic. For example, the basket is characterized by a simple structure, lightweight design, and convenient operation; the basket is mainly used in long-span, pre-stressed concrete cantilever beams, continuous beams, and rigid frame bridges (Yepes et al., 2020).

2.3. Modeling of construction methods

Methods were affected by the complexity of bridge engineering design, the aesthetics of the installation, the particularity of the structure, and other factors (Molina-Moreno et al., 2017); many influencing factors such as environment, cost, safety, construction period, and so on need to be considered in the construction. Bridges in highway engineering are limited by landscape area, structural function, and surrounding environment. Under the guidance of cost minimization and meeting the design specifications, the construction personnel needs to pay more attention to the life cycle sustainability of the system (Yoon et al., 2018). Industrial production enables tight control of energy consumption, enabling sustainable, optimized designs (Moussavi Nadoushani & Akbarnezhad, 2015).

With the successful development of the world economy, new standards for bridge shape, environmental compatibility, and landmark buildings have been established to satisfy the durability of a structure (Rinke, 2018). Subsequently, long-span, complex, structural system conversion, and high-standard and advanced construction machinery are used to solve these problems (Li et al., 2020).

As shown in Figure 3, materials, equipment, and labour are three significant elements of the construction industry (García-Segura et al., 2018). No matter which construction method is adopted, three factors are indispensable. Simultaneously, energy consumption and environmental carbon emissions are closely linked to the three factors. This study is based on analysing the dynamic changes of the three factors. Unlike traditional construction, industrialized construction adds a factory to prefabricate the assembly components required for the bridge. Then the prefabricated parts are transported and installed in a unified manner using modern, large-scale mechanical equipment. This practice improves labour efficiency and product quality, ensures safety, and reduces costs, waste, and environmental pollution (Othuman Mydin et al., 2014).

2.3.1. Process model analysis of prefabrication and installation

Bridge components are prefabricated to save costs and reduce environmental impact. After the project site survey and contract negotiation, the existing prefabricated component factory was used to replace some equipment and machinery and then directly put into production to manufacture bridge components for the project (Durdyev & Ismail, 2019).

The environmental impacts of prefabrication plants mainly include the following aspects: the factory for prefabrication; materials during the construction and production of the factory for prefabrication; vehicles during the construction and presentation of the factory for prefabrication; equipment and types of machinery during the construction and production of the factory for prefabrication; construction personnel during the construction personnel of the factory for prefabrication; personnel energy consumption; the structure of the factory for prefabrication and environmental impact during the prefabrication production (Tchidi et al., 2012).

The emerging technologies constantly accelerated the construction of bridges and reduced the replacement and repair time of old and new bridges built on site. Prefabricated bridge members and systems are essential solutions, superior in easy installation and fast construction on-site. Compared with a traditional cast-in-place structure, it can improve the production intensity significantly (e.g., compressive strength and tensile strength), long-term stability (e.g., creep and shrinkage), and durability (e.g., chloride penetration and freeze-thawing) (Pons et al., 2018).

Figure 4 shows the installation process of the highway bridge structure. A broader and prefabricated hoisting area shall be provided for unique bridges that span rivers, oceans, and deep valleys (e.g., cable-stayed bridges, suspension bridges, arch bridges, long-span box girder bridges), guarantee construction quality and safety. If it is hard to satisfy the prefabricated hoisting conditions, on-site concrete pouring schemes are generally adopted (Huang et al., 2019; He et al., 2020).

2.3.2. Determination of core impact indicators

Teng et al. (2017) established the industrialized building symbiosis model and divided it into concept definition period, design period, construction period, and in-use period. Wang et al. (2018) assessed the risk level of industrialized building projects with a meta-network risk management model. They proposed corresponding risk control measures through risk identification, analysis and assessment, and processing and control (Zhou, 2021).

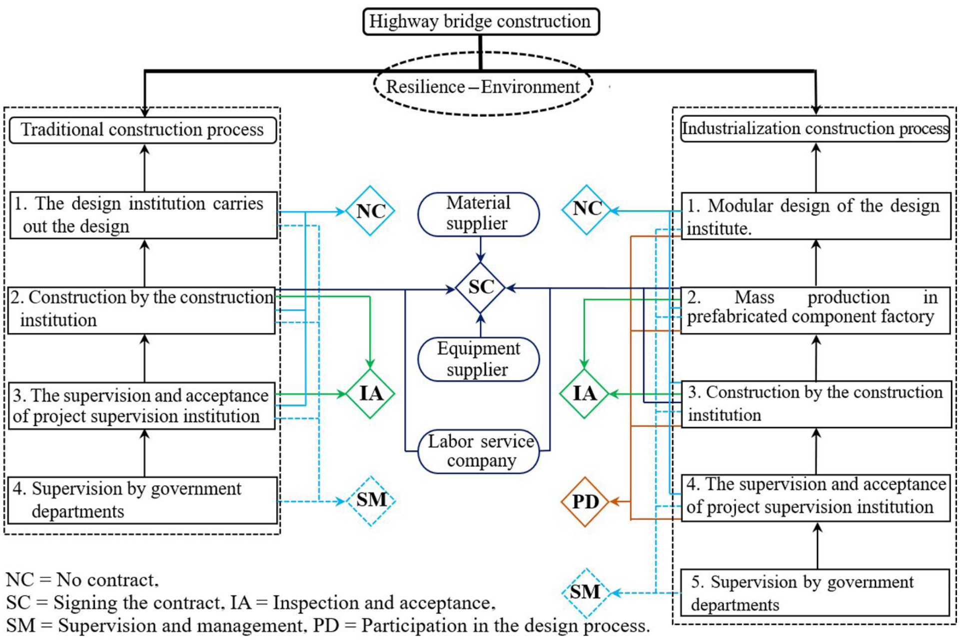

Figure 3. Diagram of traditional building and industrialized building process

The whole life cycle evaluation model of China's construction industrialization and traditional construction methods is studied, with reference significance and case study value.

The manufacture, application, and disposal of bridge materials are the main threats to the rapid depletion of natural resource reserves and other environmental problems such as climate change and are also the focus of researchers. The contents that need to be analysed throughout the life cycle are five metrics: materials of the building; vehicles of construction; mechanical equipment; all consumption of construction personnel; energy consumption by building (Figures 4 and 5). According to the five influencing factor indexes obtained from the analysis, a mathematical model of resilience theory under two different architectural models (prefabrication and installation) is established (for the analysis of the mathematical resilience model, see 2.3.3).

2.3.3. The establishment of resilience theoretical model

Figure 5 shows the changes in the resilience parameters of the environmental impact factors during the construction stage of the bridge life cycle (represented by the red straight line). The five influencing factors are accompanied by two different construction and installation methods, and the resilience factor changes, as shown in Figure 5. The environmental impact ratio is determined based on Zhou et al. (2021a). The research model and the bridge structure are robust, and the proportion of materials and equipment is more significant (Section 3). The time nodes $\left(T_{1_{1N}}, T_{1_{11}}\right)$ are shown in Figure 5. Over time, the resilience in five impact categories changes during the construction and installation stages. The total quantity of construction materials used in the two construction methods is the same, and the contribution progress of environmental impact generated is the same (E_{material} is the same).

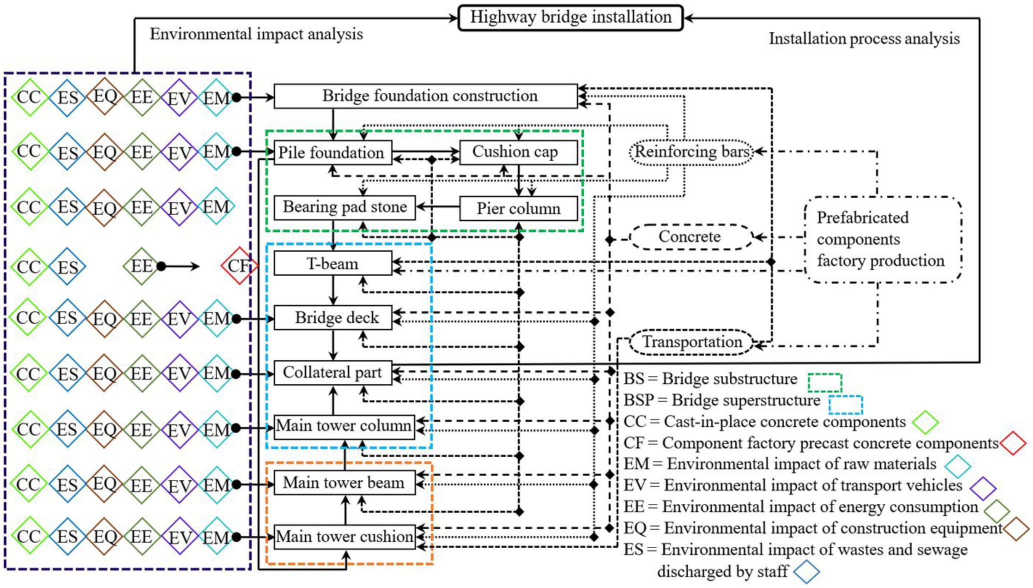

Figure 4. Diagram of installation process and environmental impact model analysis of the entire network bridge

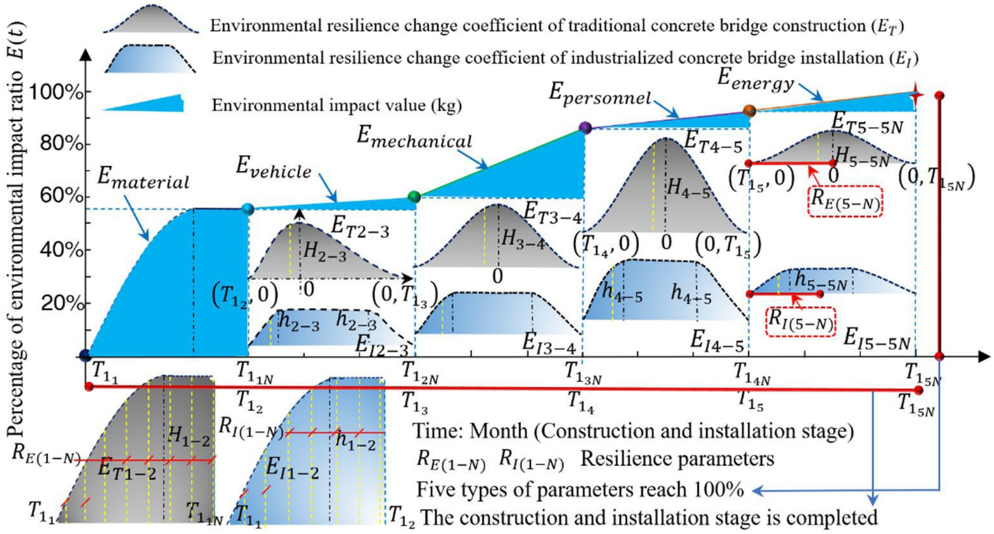

Figure 5. Resilience analysis: resilience parameters of traditional concrete bridges and industrialized concrete bridges

Equations (2), (3) are used to analyse the interaction between the changes in resilience parameters and environmental impact factors. The arc area formed by the parabola is 2/3 of the product of the chord length of the arc triangle and the height H (Han et al., 2019).

$$\sum_{E_{T1}}^{E_{TN}} E_{\text{bridge}} =$$

$$\begin{bmatrix} E_{T1-2} & H_{1-2} & \left[\left(T_{1_1} \le R_{E(1-2)} < 0\right),\left(0 < R_{E(1-2)} \le T_{1_2}\right)\right] & \left\{\left(T_{1_2} - T_{1_1}\right) + \left[T_{1_2} - R_{E(1-2)}\right]\right\} \times H_{1-2}/2 \\ E_{T2-3} & H_{2-3} & \left[\left(T_{1_2} \le R_{E(2-3)} < 0\right),\left(0 < R_{E(2-3)} \le T_{1_3}\right)\right] & \frac{2}{3}\left\{H_{2-3} \times \left[\sum_{T=T_{1_2}}^{T=T_{1_N}} \left(T_{1_{N-N+1}}\right)\right]\right\} \\ E_{T3-4} & H_{3-4} & \left[\left(T_{1_3} \le R_{E(3-4)} < 0\right),\left(0 < R_{E(3-4)} \le T_{1_4}\right)\right] & \frac{2}{3}\left\{H_{3-4} \times \left[\sum_{T=T_{1_3}}^{T=T_{1_N}} \left(T_{1_{N-N+1}}\right)\right]\right\} \\ E_{T4-5} & H_{4-5} & \left[\left(T_{1_4} \le R_{E(4-5)} < 0\right),\left(0 < R_{E(4-5)} \le T_{1_5}\right)\right] & \frac{2}{3}\left\{H_{4-5} \times \left[\sum_{T=T_{1_4}}^{T=T_{1_N}} \left(T_{1_{N-N+1}}\right)\right]\right\} \\ E_{T5-N} & H_{5-N} & \left[\left(T_{1_5} \le R_{E(5-N)} < 0\right),\left(0 < R_{E(5-N)} \le T_{1_N}\right)\right] & \frac{2}{3}\left\{H_{5-N} \times \left[\sum_{T=T_{1_5}}^{T=T_{1_N}} \left(T_{1_{N-N+1}}\right)\right]\right\} \end{bmatrix}, \quad (4)$$

E_{T1-2}, E_{T5-N} are environmental impact of cast-in-place bridge in each stage (kg); H_{1-2}, H_{5-N} are chord height of environmental impact parabola of each stage (kg); $R_{E(1-2)}$, $R_{E(5-N)}$ are environmental resilience change coefficient of cast-in-place bridge in each stage.

$$\sum_{E_{I1}}^{E_{IN}} E_{\text{bridge}} =$$

$$\begin{bmatrix} E_{I1-2} & H_{1-2} & \left[\left(I_{1_1} \le R_{I(1-2)} < 0\right),\left(0 < R_{I(1-2)} \le I_{1_2}\right)\right] & \left\{\left(I_{1_2} - I_{1_1}\right) + \left[I_{1_2} - R_{I(1-2)}\right]\right\} \times H_{1-2}/2 \\ E_{I2-3} & H_{2-3} & \left[\left(I_{1_2} \le R_{I(2-3)} < 0\right),\left(0 < R_{I(2-3)} \le I_{1_3}\right)\right] & \left\{\left(I_{1_3} - I_{1_2}\right) + \left[I_{1_3} - R_{I(2-3)}\right]\right\} \times H_{2-3}/2 \\ E_{I3-4} & H_{3-4} & \left[\left(I_{1_3} \le R_{I(3-4)} < 0\right),\left(0 < R_{I(3-4)} \le I_{1_4}\right)\right] & \left\{\left(I_{1_4} - I_{1_3}\right) + \left[I_{1_4} - R_{I(3-4)}\right]\right\} \times H_{3-4}/2 \\ E_{I4-5} & H_{4-5} & \left[\left(I_{1_4} \le R_{I(4-5)} < 0\right),\left(0 < R_{I(4-5)} \le I_{1_5}\right)\right] & \left\{\left(I_{1_5} - I_{1_4}\right) + \left[I_{1_5} - R_{I(4-5)}\right]\right\} \times H_{4-5}/2 \\ E_{I5-N} & H_{5-N} & \left[\left(I_{1_5} \le R_{I(5-N)} < 0\right),\left(0 < R_{I(5-N)} \le I_{1_N}\right)\right] & \left\{\left(I_{1_N} - I_{1_5}\right) + \left[I_{1_N} - R_{I(5-N)}\right]\right\} \times H_{5-N}/2 \end{bmatrix}, \quad (5)$$

E_{I1-2}, E_{I5-N} are environmental impact of industrialized bridge installation in each stage (kg); $R_{I(1-2)}$, $R_{I(5-N)}$ are resilience change coefficient of industrialized precast bridge in each stage.

Equations (4) and (5) are the mathematical theoretical models for the environmental impact and environmental resilience parameter changes of cast-in-place, concrete bridges, and industrialized precast bridges. The theoretical model system establishes two sets of theoretical models according to the constraints of two different construction methods. Each set of models is affected by the resilience of five factors and presents different resilience curves. Each resilience curve has been determined by two parameters: E_T and H_N (see Figure 5).

3. Results and discussion

The case study is the large span bridge over China's Shang Hai-Cheng Du G50 Expressway. Tie Luo Ping Bridge. The bridge holes were arranged as 6 × 30 + 140 + 322 + 140 + 3 × 30 m (Figure 6). The main bridge is a 140 + 322 + 140 m, three-span and one-binding pre-stressed concrete, cable-stayed bridge, installed with two towers and double cable planes. The overall width of the main beam is 27.5 m, the end height is 2.6 m, and the center height is 2.875 m; the top plate of the main shaft is 0.31 m thick. The length of the sections is divided into 8.0m and 5.2 m. The width of edge ribs is divided into 1.7 m, 3.0 m, 3.5 m, and 5 m. The essential spacing of the beams is 8.0 m and 5.2 m, respectively, and the connection between the central tower and the main shaft is more consolidated. The upper structure of the auxiliary bridge on both banks is a 30 m, post-tensioned, pre-stressed concrete T-beam with a height of 1.8 m. Five T-beams are arranged in each hole for the half-span bridge, and the beam spacing is 2.5 m.

In this study, multiple influencing factors in the construction industry are selected. The models are designed, meaning that the research is scientific and representative (Zhou et al., 2020b). The authors are selecting an extra-large twin-tower cable-stayed bridge as the research object further increases the research's robustness and paradigm.

3.1. Case parameters

The construction duration of the Tie Luo Ping Bridge was 760 days. The pile foundations, pile caps, and pier studs were constructed with cast-in-place concrete. The height of No. 7 and No. 8 main towers of the cable-stayed bridge was 190.397 m, and the pier stud concrete was poured by hydraulic self-climbing formwork (Figure 7a). The pouring length of each standard section was 6 m, and the pouring operation was conducted 32 times (10 days to complete a concrete pouring cycle). The central tower was designed with one beam (pre-stressed single-box structure, clear span 27.5 m, width 6.1 m, and height 6.00–6.28 m) at 103.025 m and 158.897 m, respectively. Both the upper and lower beams were cast-in-place with the bracket supported. One tower crane and one elevator were erected at No. 7 and No. 8 (Figures 7c, 7d), respectively, to provide transportation and construction convenience. HBT60 and HBT80 pumped the concrete of the tower column, and the transmission pipeline was 200 m long. A mixing station was built at numbers 6 and 9 to produce the concrete used for the bridge construction. One backup generator was equipped at No. 6, 7, 8, and 9 towers, respectively, to prevent power outages.

No. 0, 1* beam sections (Symmetrical position), and No. 21 of the cable-stayed bridge's main beam were cast in place with pier-side brackets; the construction duration lasted 45 days. No. 2 to 19 and 2* to 19* beam sections (symmetrical position (Figure 7e)), adopted the front pivot basket casting, and the construction duration was 15 days. The weight of every single empty basket was 200 T, and four baskets were installed, with two baskets installed for No. 7 and 8, respectively. No. 20 and 20* beam sections are closure sections, all of which were constructed with hanging brackets. Each hanging rack weighed 60 T and was in two groups (Figure 7b). The T beam of the auxiliary bridge was constructed by the industrialized and prefabricated hoisting method (T-beam prefabrication).

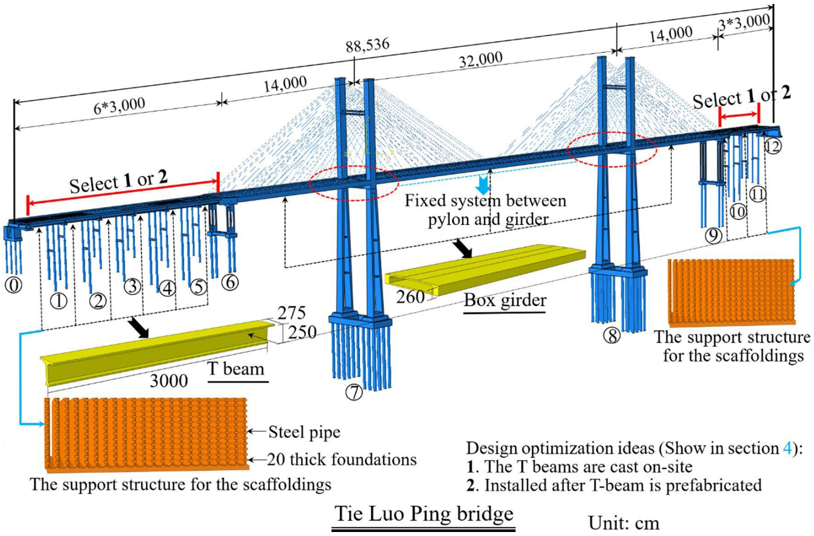

Figure 6. Plane diagram of cable stayed bridge

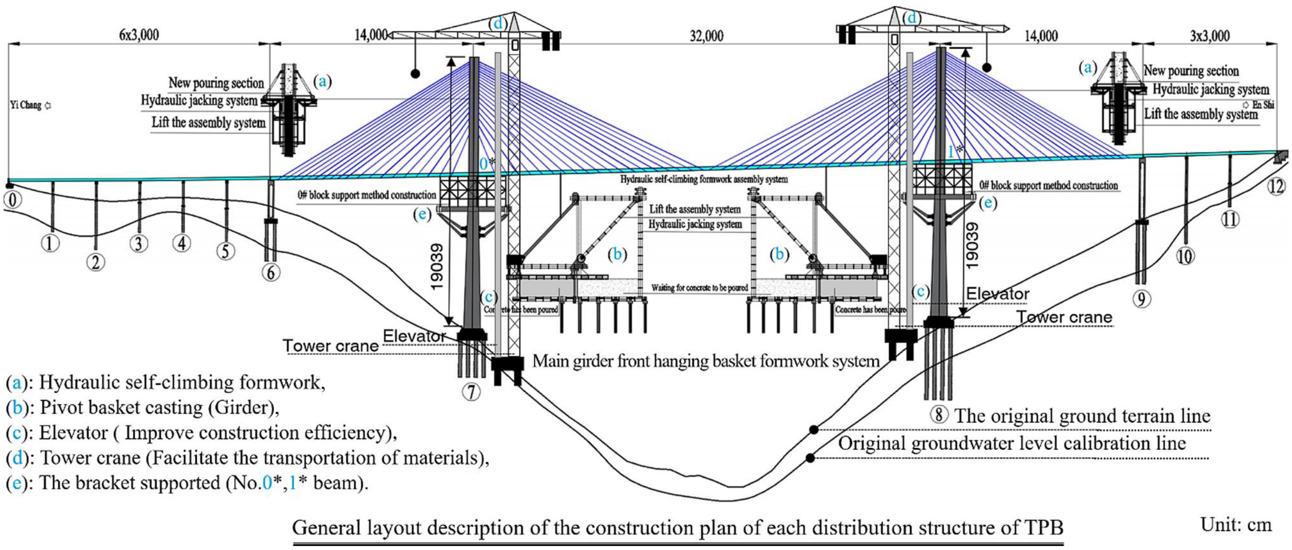

Figure 7. Facade display of Tie Luo Ping Bridge's large-scale equipment and construction machines

3.2. Influence area

The bridge was selected as the case because of its special research significance. The central part of the bridge (beam body and tower body) embodies an effective combination of industrialized installation and cast-in-place construction. The

bridge is a long-span, cable-stayed bridge with very high piers constructed in a complex area, which is significant in studying environmental resilience.

Figure 8 shows the project management process of each link in the bridge construction, the entire construction period, and the schedule of each construction link. The principle of project management is to meet the safety and quality requirements and commence the construction work as scheduled. The first set has 12 nodes, and the total planning duration is 233 days; the second set has 12 nodes, and the complete planning duration is 234 days; the third set has 14 nodes (the purple line indicates), and the whole planning duration is 625 days. The fourth set has13 nodes, and the planning duration is 615 days. The most critical route is matched with the third set of project management plans, the optimal strategy. The main bridge pier studs (numbers 6, 9) in the interval 8–10 were 180 days, accounting for 23.7% of the total construction duration. The construction duration of the baskets of the seven # and eight # main beams in the interval 12–19 and interval 13–20 was 230 days, accounting for 30.2% of the total construction duration. Data analysis proves that these two intervals are the main intervals for the distribution of the environmental resilience impact.

The key lines affecting the construction phase are: 01 →02→03→07→08→10→12→16→19→21→23→28→31→32 (the critical data analysis part in 3.3).

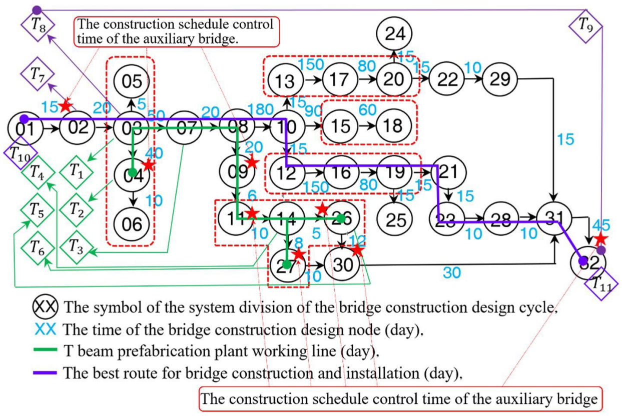

Figure 8. Project management: Design plan for bridge project construction management
(Optimal route analysis of dual-code network)

3.3. Environmentally resilience

Compared with other industries, the construction industry is a high-risk industry characterized by a poor working environment, complex situations, high labour turnover rate, et al., effectively reducing environmental pollution (Zhang et al., 2020). In the design and research process of the complete text, the best and green ideas are selected to complete the model and data analysis.

In the research and analysis, the construction materials of the temporary construction facilities in the mixing station, the prefabricated beam field, and the project management office area are all environmentally-friendly (Zhang et al., 2020), making the database data more complete.

According to Figures 3 and 4, and Eqns (4) and (5), the formulas are shown below:

$$\sum_{E_{T1}}^{E_{TN}} E_{T\text{ beam precast yard}} =$$

$$\sum_{T_1}^{T_2}\begin{bmatrix} E_{\text{Material}} & H_{M1} & T_0 < R_{IM1} \le T_{40} \\ E_{\text{Vehicle}} & H_{v1} & T_0 < R_{IM1} \le T_{40} \\ E_{\text{Mechanical}} & H_{m1} & T_0 < R_{IM1} \le T_{40} \\ E_{\text{Personnel}} & H_{p1} & T_0 < R_{IM1} \le T_{40} \\ E_{\text{Energy}} & H_{e1} & T_0 < R_{IM1} \le T_{40} \end{bmatrix}$$

$$\bigcup\sum_{T_3}^{T_4}\begin{bmatrix} E_{\text{Material}} & H_{M2} & T_{41} < R_{IM2} \le T_{106} \\ E_{\text{Vehicle}} & H_{v2} & T_{41} < R_{IM2} \le T_{106} \\ E_{\text{Mechanical}} & H_{m2} & T_{41} < R_{IM2} \le T_{106} \\ E_{\text{Personnel}} & H_{p2} & T_{41} < R_{IM2} \le T_{106} \\ E_{\text{Energy}} & H_{e2} & T_{41} < R_{IM2} \le T_{106} \end{bmatrix}$$

$$\bigcup\sum_{T_5}^{T_6}\begin{bmatrix} E_{\text{Material}} & H_{M3} & T_{107} < R_{IM3} \le T_{117} \\ E_{\text{Vehicle}} & H_{v3} & T_{107} < R_{IM3} \le T_{117} \\ E_{\text{Mechanical}} & H_{m3} & T_{107} < R_{IM3} \le T_{117} \\ E_{\text{Personnel}} & H_{p3} & T_{107} < R_{IM3} \le T_{117} \\ E_{\text{Energy}} & H_{e3} & T_{107} < R_{IM3} \le T_{117} \end{bmatrix} =$$

$$\sum_{T_1}^{T_2}\begin{bmatrix} E_{\text{Material}} & 1893.8 & 0 < R_{IM1} \le 71.02 \\ E_{\text{Vehicle}} & 11.53 & 0 < R_{IM1} \le 0.43 \\ E_{\text{Mechanical}} & 79.73 & 0 < R_{IM1} \le 2.99 \\ E_{\text{Personnel}} & 4.91 & 0 < R_{IM1} \le 0.18 \\ E_{\text{Energy}} & 5.51 & 0 < R_{IM1} \le 0.21 \end{bmatrix}$$

$$\bigcup\sum_{T_3}^{T_4}\begin{bmatrix} E_{\text{Material}} & 4{,}876.8 & 71.02 < R_{IM2} \le 112.54 \\ E_{\text{Vehicle}} & 80.59 & 0.43 < R_{IM2} \le 1.86 \\ E_{\text{Mechanical}} & 421.96 & 2.99 < R_{IM2} \le 9.74 \\ E_{\text{Personnel}} & 38.53 & 0.18 < R_{IM2} \le 0.89 \\ E_{\text{Energy}} & 49.58 & 0.21 < R_{IM2} \le 1.15 \end{bmatrix}$$

$$\bigcup\sum_{T_5}^{T_6}\begin{bmatrix} E_{\text{Material}} & 0.024 & 112.54 \ge R_{IM3} \ge 0.007 \\ E_{\text{Vehicle}} & 150.81 & 1.86 < R_{IM3} \le 45.24 \\ E_{\text{Mechanical}} & 262.21 & 9.74 < R_{IM3} \le 78.66 \\ E_{\text{Personnel}} & 14.95 & 0.89 < R_{IM3} \le 4.49 \\ E_{\text{Energy}} & 4.72 & 1.15 < R_{IM3} \le 1.42 \end{bmatrix}, \quad (6)$$

$T_1 = T_{\text{PCS}}$ (PCS is plant construction start); $T_2 = T_{\text{PCC}}$ (PCC is plant construction completed); $T_3 = T_{\text{FPS}}$ (FPS is factory production started); $T_4 = T_{\text{EFP}}$ (EFP is end of factory production); $T_5 = T_{\text{TBIB}}$ (TBIB is T beam installation begins); $T_6 = T_{\text{ETBI}}$ (ETBI is end of T beam installation); R_{IM1}, R_{IM2}, R_{IM3} are resilience changes in T beam environmental factors.

$$\sum_{E_{T7}}^{E_{T9}} E_{\text{CMP}} =$$

$$\sum_{T_7}^{T_8}\begin{bmatrix} E_{\text{Material}} & H_{M4} & T_0 < R_{IM4} \le T_{20} \\ E_{\text{Vehicle}} & H_{v4} & T_0 < R_{IM4} \le T_{20} \\ E_{\text{Mechanical}} & H_{m4} & T_0 < R_{IM4} \le T_{20} \\ E_{\text{Personnel}} & H_{p4} & T_0 < R_{IM4} \le T_{20} \\ E_{\text{Energy}} & H_{e4} & T_0 < R_{IM4} \le T_{20} \end{bmatrix}$$

$$\bigcup\sum_{T_8}^{T_9}\begin{bmatrix} E_{\text{Material}} & H_{M5} & T_{21} < R_{IM5} \le T_{760} \\ E_{\text{Vehicle}} & H_{v5} & T_{21} < R_{IM5} \le T_{760} \\ E_{\text{Mechanical}} & H_{m5} & T_{21} < R_{IM5} \le T_{760} \\ E_{\text{Personnel}} & H_{p5} & T_{21} < R_{IM5} \le T_{760} \\ E_{\text{Energy}} & H_{e5} & T_{21} < R_{IM5} \le T_{760} \end{bmatrix} =$$

$$\sum_{T_7}^{T_8}\begin{bmatrix} E_{\text{Material}} & 2{,}676.33 & 0 < R_{IM4} \le 200.73 \\ E_{\text{Vehicle}} & 34.72 & 0 < R_{IM4} \le 2.61 \\ E_{\text{Mechanical}} & 82.39 & 0 < R_{IM4} \le 6.18 \\ E_{\text{Personnel}} & 3.69 & 0 < R_{IM4} \le 0.28 \\ E_{\text{Energy}} & 4.13 & 0 < R_{IM4} \le 0.31 \end{bmatrix}$$

$$\bigcup\sum_{T_8}^{T_9}\begin{bmatrix} E_{\text{Material}} & 461.93 & 200.73 \ge R_{IM5} \ge 1.88 \\ E_{\text{Vehicle}} & 627.46 & 2.61 \ge R_{IM5} \ge 2.55 \\ E_{\text{Mechanical}} & 651.48 & 6.18 \ge R_{IM5} \ge 2.65 \\ E_{\text{Personnel}} & 47.74 & 0.28 \ge R_{IM5} \ge 0.19 \\ E_{\text{Energy}} & 273.66 & 0.31 < R_{IM5} \le 1.11 \end{bmatrix}; \quad (7)$$

$$\sum_{E_{T10}}^{E_{T11}} \text{BCI} =$$

$$\sum_{T_{10}}^{T_{11}}\begin{bmatrix} E_{\text{Material}} & H_{M6} & T_0 < R_{IM6} \le T_{760} \\ E_{\text{Vehicle}} & H_{v6} & T_0 < R_{IM6} \le T_{760} \\ E_{\text{Mechanical}} & H_{m6} & T_0 < R_{IM6} \le T_{760} \\ E_{\text{Personnel}} & H_{p6} & T_0 < R_{IM6} \le T_{760} \\ E_{\text{Energy}} & H_{e6} & T_0 < R_{IM6} \le T_{760} \end{bmatrix} =$$

$$\sum_{T_{10}}^{T_{11}} \begin{bmatrix} E_{\text{Material}} & 127{,}099.52 & 0< R_{IM6} \le 501.71 \\ E_{\text{Vehicle}} & 903.41 & 0< R_{IM6} \le 3.57 \\ E_{\text{Mechanical}} & 9{,}651.87 & 0< R_{IM6} \le 38.10 \\ E_{\text{Personnel}} & 493.79 & 0< R_{IM6} \le 1.95 \\ E_{\text{Energy}} & 8{,}888.16 & 0< R_{IM6} \le 35.08 \end{bmatrix}, \quad (8)$$

E_{CMP} is E data of concrete mixing plant; T_7 is T beam data of Construction of concrete mixing plant started; T_8 is data of the construction of the concrete mixing plant is completed; T_9 is data of the supply stage of the concrete production of the mixing plant; R_{IM4}, R_{IM5}, R_{IM6} are resilience changes in concrete mixing station environmental factors; T_{10} is data of construction and installation of the bridge begins; T_{11} is data of bridge construction and installation are over.

Based on Eqns (7) and (8), the environmental resilience value of the bridge can be represented as:

$$\sum_{E_1}^{E_N} E_{\text{bridge}} = \bigcup_{T_N}^{I_N} \left(\sum_{E_{T1}}^{E_{TN}} E_{\text{bridge}} + \sum_{E_{I1}}^{E_{IN}} E_{\text{bridge}} \right) =$$

$$\bigcup_{T_N}^{I_N} \left(\sum_{E_{T1}}^{E_{TN}} E_{\text{TBPY}} + \sum_{E_{T7}}^{E_{T9}} \text{E}_{\text{CMP}} + \sum_{E_{T10}}^{E_{T11}} E_{\text{BCI}} \right), \quad (9)$$

TBPY is T beam precast yard; CMP is concrete mixing plant; BCI is bridge construction and installation.

As shown in Figure 9a, the material environmental resilience factor for the T-beam factory for prefabrication changes significantly. In the production stage, the ecological resilience factor increased to 112.54. However, it decreased to 0 in the installation stage, related to the emissions caused by extracting the raw materials required for steel and concrete production. In the installation stage, the output of T-beams tends to end, so the value is nearly zero. The environmental resilience factor of the equipment reaches a peak of 78.66 during the installation of large kits, such as bridge erecting machines, beam transport trolleys, and gantry cranes are used. The change rates of environmental resilience factors are in the range of $\varphi_2 > \varphi_3 > \varphi_4 > \varphi_1$.

The maximum resilience modulus of the concrete batching plant is 200.73 (Figure 9b). With the construction process, the amount of concrete was gradually reduced, and the resilience modulus dropped to 1.88. The changing function of the resilience modulus vividly shows the workflow of the mixing plant. The mixing plant needs to reserve 49,702.4 m^3 of concrete for production. The time interval is 760 days, which is the construction design cycle. The changes in the other four resilience parameters are relatively low.

As shown in Figure 9c, the material's resilience modulus in the construction stage reaches 501.71, and the installation and use of many materials such as bridge reinforcement and steel strands (concrete is included in the concrete batching plant stage) maximize the environmental impact. Much of the construction equipment has been used, resulting in a high resilience coefficient of 38.1. It mainly includes large excavators, asphalt pavers, tower cranes, small steel bar processing equipment, and tensioning equipment.

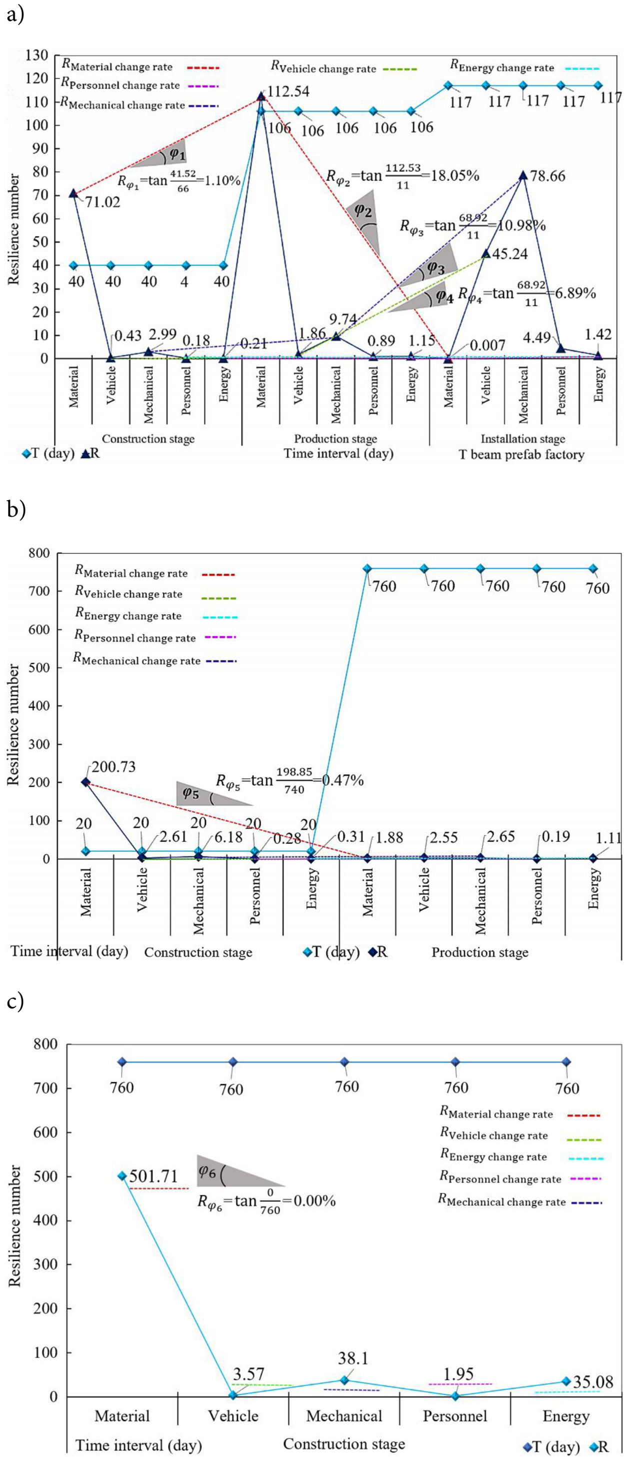

Figure 9. The resilience coefficient: a – The resilience coefficient changes in T beam precast stages; b – Analysis of the resilience coefficient changes in concrete mixing plant stages; c – Analysis of the resilience coefficient changes in project construction stages

As shown in Table 1, the environmental impacts generated during the construction and installation stages of the bridge are up to 197,527.24 t, which are mostly caused by the emissions from the materials and equipment. The emissions caused by manufacturing the reinforcement bars, steel, and anti-corrosion coatings accounted for 93.7% of the total emissions (bridge concrete consists of

Table 1. Statistical table of the resilience analysis of the bridge's environmental impact

Project	Concrete mixing plant (kg)	T beam (kg)	Engineering construction process (kg)
Material	48,869,474.08	6,770,725.23	127,099,517.80
Vehicle	662,183.49	242,931.59	903,408.93
Mechanical	733,877.37	763,887.85	9,651,868.49
Personnel	51,421.50	58,399.18	493,786.80
Energy	277,791.25	59,807.52	888,162.22

T-beam concrete and cast-in-place concrete, which are classified in the analysis of the beam yard and the mixing station, respectively). The environmental impact contributed by the T-beam factory during prefabrication is 7,895.75 t. The concrete used for beam yard curing and the concrete used for T-beam production accounted for 48.9% of the total emissions of the beam yard; the T-beam rebars and steel strands accounted for 36.0% of the total emissions of the beam yard. The environmental impact generated by the concrete mixing station is 50,594.75 t. The concrete used for site curing of the mixing station and the concrete casting accounted for 66.9% of the total emissions of the mixing station.

The 90 T-beams of the Tie Luo Ping Bridge's approach were produced in the beam yard and then transported to the project site by a beam truck for a span-by-span erection using a bridge girder-erecting machine. The erection duration was 13 days, generating 432.68 t of emissions, which accounted for 5.48% of the total emissions from the beam yard and 0.22% of the total emissions from the bridge, respectively.

In contrast, cement, the primary raw material for concrete, accounted for 32.3% of the total emissions of the mixing station. Cement production accounted for 8–10% of total global CO_2 emissions. Hence, green cement manufacturing with low energy consumption, high performance, and lifetime sustainability is critical (Suhendro, 2014).

As shown in Figure 10, the pollution generated by materials in the three stages has a more significant proportion. The early part of each stage makes the most significant contribution to the environmental resilience impact of materials; the growth rate of material emissions after completing the main structure of the project levels off, reaching the peak. With the construction progress of each sub-project and sub-divisional work on the project, the energy consumption of vehicles, equipment and construction personnel present a secondary parabolic change against the environmental resilience impact. Furthermore, there is no more change after reaching a saturated state (the project's construction progress, quality, and safety conditions are met). After the sub-projects and sub-divisional works were completed, the supporting vehicles, types of machinery, and personnel left the project site, and the construction tasks were concluded. The pollution discharge gradually reduced until it reached zero.

The trend analysis of the project management process shows that all the three management processes are growing in a quadric trend, and there is no sudden change in the area. The conclusion conforms to the principle of robustness:

y_C = 0.0022x^4 – 0.0258x^3 + 0.1351x^2 – 0.2711x + 0.1966 (goodness of fit: R^2 = 1, the fitting conclusion is accurate).

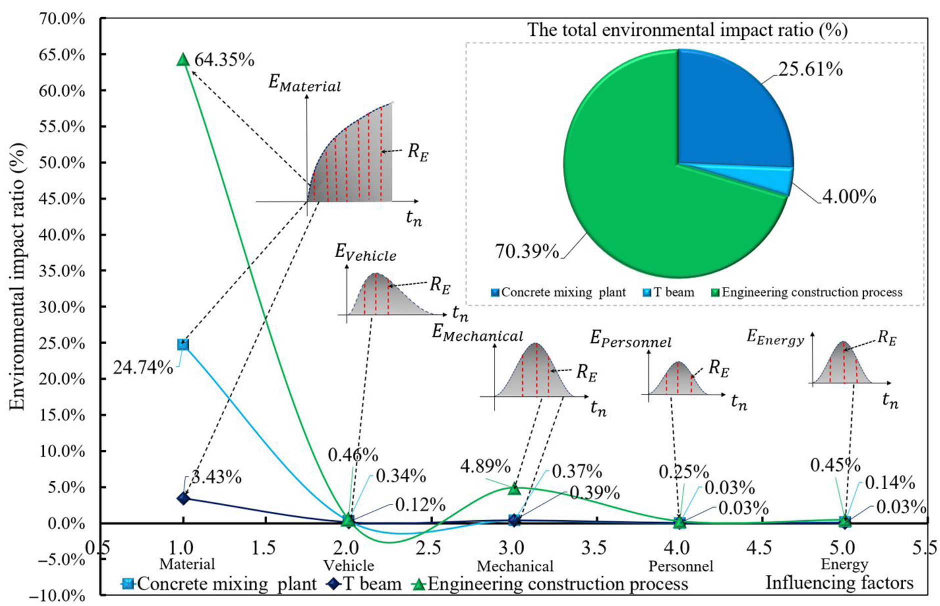

Figure 10. Diagram of the analysis of five resilience indicators of bridge environmental impact

y_T = 0.0107x^4 – 0.1483x^3 + 0.7447x^2 –1.6005x + 1.2408 (R^2 = 1).

y_E = 0.038x^4 – 0.5093x^3 + 2.4466x^2 – 4.9841x + 3.6522 (R^2 = 1).

After the above equations are obtained by applying the fitting algorithm, Wolfram Mathematica 12.1 software is used to prove the robustness of Figures 9 and 10 and the conclusions according to the compiled data program.

In Figure 11, the authors analyse the resilience changes of five influencing factors under the two modes. After completing the case data analysis, we again demonstrate the robustness of the resilience research. According to the analysis data in Table 2, we compiled MATLAB, Wolfram Mathematica scientific algorithm program to draw a figure of environmental resilience. Also, complete the mathematical models of the five influencing factors under the two construction modes. Readers can verify that the research model proposed in Figure 5 has the best robustness and paradigm through each type of theoretical mathematical model in Figure 11. Advocating management innovation in the engineering construction process is an effective strategy to improve the sustainable development goals of the construction industry (Zhou et al., 2021b).

4. Response of resilient design

Section 3 discusses how to make a reasonable and practical resilience response to the construction and installation stage under the constraints of the normative system in the research area. Table 2 shows that materials take up a more significant proportion of environmental impacts under two different construction modes. The original design of No. 0–6 bridges and No. 9–12 T-beams was completed by industrialized production + on-site installation and construction. In the calculation and analysis of Table 1, the T-beam produced by the bridge prefabrication plant generated a total of 7,895.85 t of environmental pollution emissions. The bridge was designed to be cast on-site with steel pipe supports, and environmental emissions were analysed to develop the construction plan with the lowest ecological pollution. The length of each span is 30 m (Figure 6). The construction scheme of "integral casting, segmented connection" was proposed to design the cast-in-place support system, early hydration heat technology and cast-in-place construction technology (Nam et al., 2013).

Figure 6 shows the construction of the steel pipe support at No. 0–6 and No. 9–12 main beams. The concrete was poured in one event. The steel pipes with a diameter of 48 mm and a wall thickness of 3.0 mm were selected.

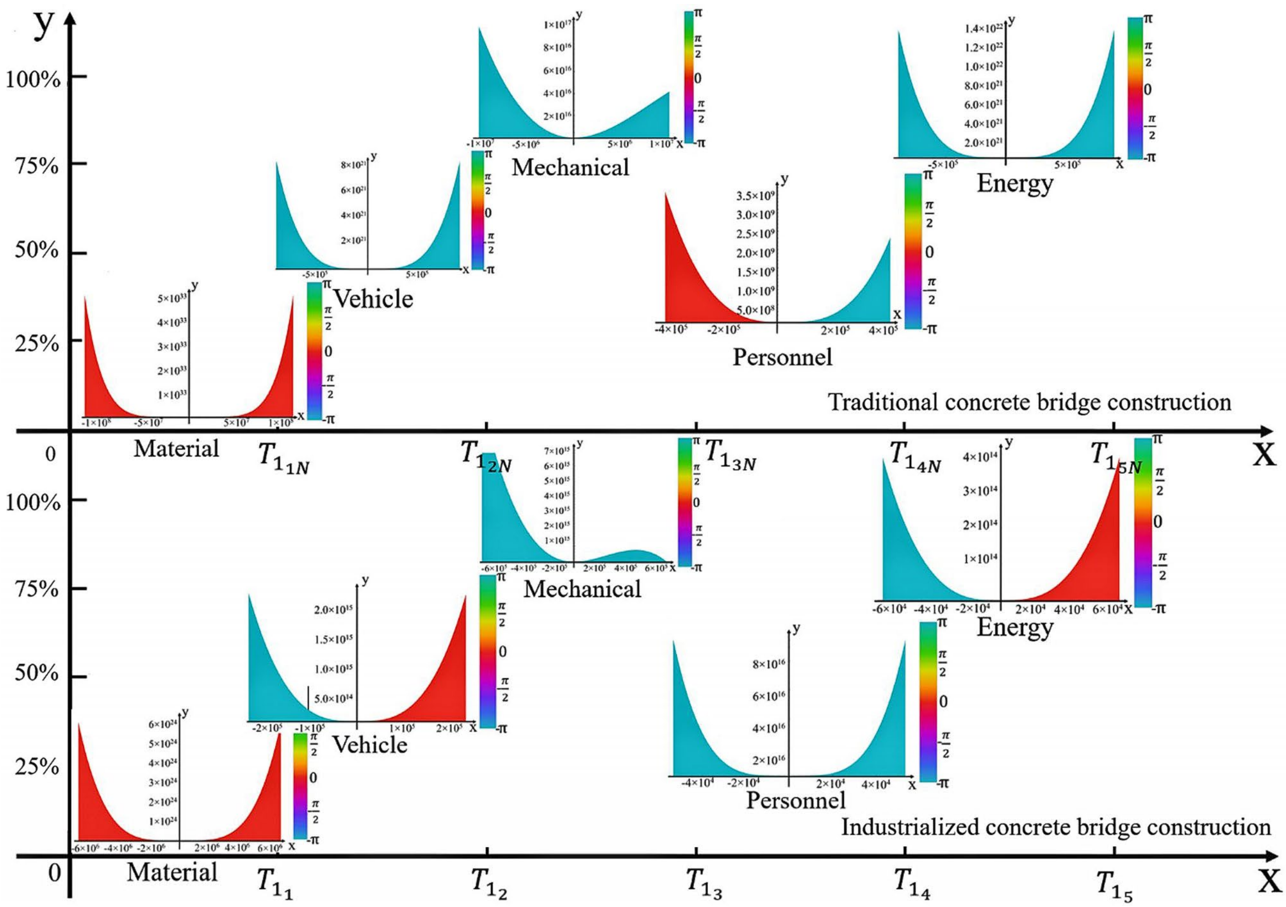

Figure 11. Project model resilience trend analysis of environmental impact of bridges

Table 2. Statistical table of environmental impact data of bridges

Name	GWP	AP	FEP	PMFP	WP
Traditional concrete bridge construction (kg)					
Material	113,332,299.20	1,384,340.77	858,833.61	3,916,441.55	7,607,602.73
Vehicle	903,056.32	257.84	59.29	33.38	2.10
Mechanical	9,651,674.47	65.50	19.67	40.46	68.39
Personnel	405,158.40	0.00	18,288.40	0.00	70,340.00
Energy	887,301.91	3.65	1.32	178.95	676.40
Total	125,179,490.30	1,384,667.75	877,202.28	3,916,694.35	7,678,689.62
Industrialized concrete bridge construction (kg)					
Material	6,503,188.61	25,206.08	16,735.60	86,163.10	139,431.85
Vehicle	242,918.58	4.52	1.50	3.08	3.90
Mechanical	763,869.54	6.23	1.92	3.95	6.20
Personnel	53,245.66	0.09	1,047.84	15.80	4,089.79
Energy	59,805.83	0.27	0.09	0.29	1.02
Total	7,623,028.22	25,217.20	17,786.95	86,186.22	143,532.77

The steel formwork with a diameter of 15 mm was used in the T-beam formwork, which was processed by the formwork factory. There are 90 beams in total.

Environmental impact of steel pipe support:

$$\sum_{L_{P=0}}^{L_{P=12}} E_{\text{Bracket}} = \sum_{L_{P=0}}^{L_{P=12}} \left[l_{\text{Bracket}} \times w_{\text{Bracket}} \times h_{\text{Bracket}} \times \lambda_s \times \left(1 \pm E_s\right) \right], \quad (10)$$

$\sum_{L_{P=0}}^{L_{P=12}} E_{\text{Bracket}}$ are environmental impact of steel pipe support (kg); l_{Bracket} is length of erection support (m) w_{Bracket} is width of erection support (m); h_{Bracket} is height of erection support (m); λ_s is environmental impact emission factor of materials (kg/kg); E_s is consumption rate of support materials (%).

The environmental impact generated the production and transportation of steel formwork is calculated.

As shown in Figure 12, No. 0–6 and No. 9–12 used the one-time, cast-in-place construction scheme by erecting steel pipe supports, resulting in 1,132,249.5 t of exhaust emissions, which is 143.4 times the total emissions of the industrialized and prefabricated installation. The substantial increase in materials generated the primary emissions. The emissions generated by the increased steel formwork were 235,899.9 t and 41,701.7 t by steel pipe support. The number of construction personnel has also increased significantly. Based on the consideration that the concrete pouring was completed at one time, the repeated use of

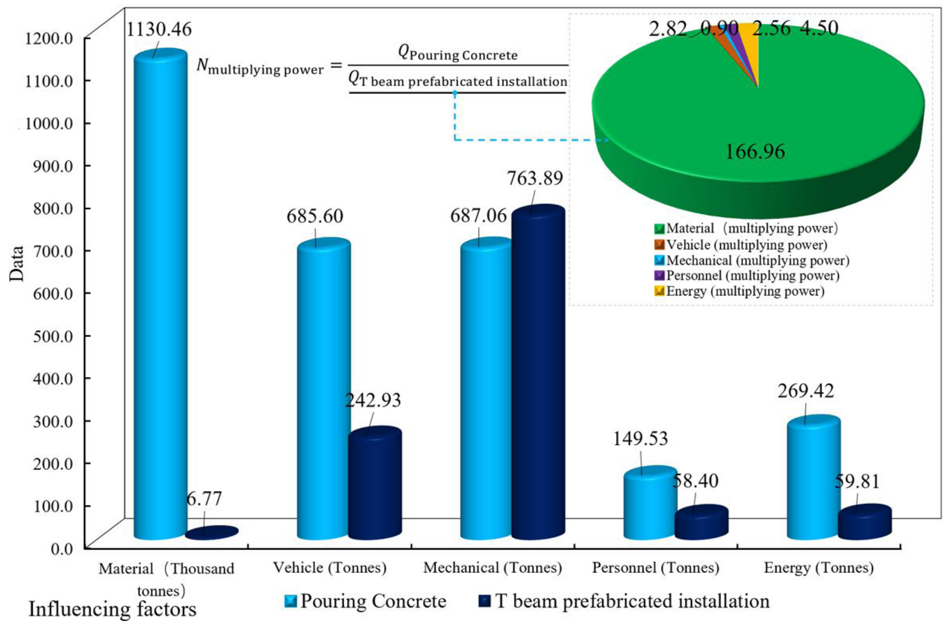

Figure 12. Comparison of environmental impact between cast-in-place construction and industrial installation of cable-stayed bridge

materials was not considered due to the limitation of the construction duration.

It can be concluded that the original design scheme is more reasonable because it can significantly reduce the pollution discharge of the project and achieve the goal of sustainable construction. The research model is validated by data analysis and mathematics and has a paradigm for evaluating the resilience change control of carbon footprint during project management.

Conclusions

Resilience theory is one of the theoretical tools for measuring and analysing the response of structural infrastructure to natural and manufactured disasters. The ability and limit of the structure to resist external force can be dynamically evaluated, and it is robust to the problem of studying discrete nonlinear characteristics.

This study analyses the environmental resilience impact changes of unique bridges during the construction duration based on resilience theory and achieves the sustainable goal of minimizing pollution through dynamic assessment and design. The combined green engineering construction, sustainable development, and environmental resilience theory lay a theoretical foundation for studying this field's resilient environmental bridge engineering evaluation. The selection of the analysis case is representative, and an extra-large bridge with complicated construction technology and construction organization design was selected for research. The robustness of the environmental resilience theoretical model is fully reflected. Moreover, for the most significant bridge, many different modes of construction, various large-scale modern machinery and equipment put into the construction, and related environmental impact resilience assessment is analysed.

The research indicates that the resilience factor of the traditional bridge construction method varies with quadratic parabola resilience, and that of the industrialized construction method varies with non-isosceles trapezoid resilience. Based on the case study, the bridge construction method is redesigned. Comparing the environmental resilience impact data produced by the two construction methods, industrial construction is 1/143 of the traditional construction method, significantly reducing the environmental pollution.

This research method has a paradigm and significant guiding value for the future environmental resilience assessment of similar super-large projects. This paper results from interdisciplinary applied (bibliometrics, solid resilience, environmental engineering, and project management) and comprehensive research. Comprehensively establish a multivariate analysis platform with "environmental dynamic resilience" as the core and innovative research theoretical models and methods. The research concludes with an extended analysis of scientific thinking and professional innovation.

In this study, the solid resilience theory was applied to analyse the environmental impact changes during the construction period of the bridge, which dynamically demonstrated the influence range of the resilience factors. Nevertheless, there are still some limitations. For example, the established resilience model has been applied in case studies in the environmental impact analysis of the construction industry, but whether it is suitable for other sectors needs to be further verified. The selected case project management mode and construction method are relatively complex. In studying the application and analysis of the theoretical model system, the researchers need to have much experience in the construction and project management of super-large bridges to apply it more appropriately.

Subsequently, we will make more efforts to study the resilience impact of the construction industry on the environment, grasp the law of change, exercise stricter control over the environmental pollution of the construction industry, and impetus sustainable development strategies.

Author contributions

Conceptualization, Z. W. Z, V. Y., and J. A.; methodology Z. W. Z.; software Z. W. Z.; validation: J. A. and V. Y.; formal analysis, Z. W. Z. and J. A.; investigation, Z. W. Z.; resources, J. A. and V. Y.; data curation, Z. W. Z.; writing-original preparation, Z. W. Z.; writing-review and editing, J. A. and V. Y.; supervision, V. Y.; project administration, J. A.; funding acquisition, V. Y.; All authors have read and agree to the published version of the manuscript.

Declaration of competing interest

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

Funding

This research was funded by the Grant PID2020-117056RB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by "ERDF A way of making Europe".

References

Bataille, C., Waisman, H., Colombier, M., Segafredo, L., Williams, J., & Jotzo, F. (2016). The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, *16*(Sup1), S7–S26. https://doi.org/10.1080/14693062.2016.1173005

Bonstrom, H., & Corotis, R. B. (2016). First-order reliability approach to quantify and improve building portfolio resilience. *Journal of Structural Engineering*, *142*(8), C4014001. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001213

Briassoulis, H. (2017). Response assemblages and their socio-ecological fit: Conceptualizing human responses to environmental degradation. *Dialogues in Human Geography*, *7*(2), 166–185. https://doi.org/10.1177/2043820617720079

Carpio, M., Ortega, J., & Prieto, A. J. (2021). Expert panel on in-situ visual inspections for masonry churches maintenance stage. *Journal of Civil Engineering and Management*, *27*(6), 454–471. https://doi.org/10.3846/jcem.2021.15256

Chen, C. (2017). Science mapping: A systematic review of the literature. *Journal of Data and Information Science*, *2*(2), 1–40. https://doi.org/10.1515/jdis-2017-0006

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Seismic resilience of a hospital system. *Structure and Infrastructure Engineering*, *6*(1–2), 127–144. https://doi.org/10.1080/15732470802663847

Durdyev, S., & Ismail, S. (2019). Offsite manufacturing in the construction industry for productivity improvement. *Engineering Management Journal*, *31*(1), 35–46. https://doi.org/10.1080/10429247.2018.1522566

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., & Klüppel, H.-J. (2006). The new international standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Life Cycle Assessment*, *11*, 80–85. https://doi.org/10.1065/lca2006.02.002

Fu, G., Zhou, S., & Qi, L. (2020). On the strain gradient elasticity theory for isotropic materials. *International Journal of Engineering Science*, *154*, 103348. https://doi.org/10.1016/j.ijengsci.2020.103348

García-Segura, T., Penadés-Plà, V., & Yepes, V. (2018). Sustainable bridge design by metamodel-assisted multi-objective optimization and decision-making under uncertainty. *Journal of Cleaner Production*, *202*, 904–915. https://doi.org/10.1016/j.jclepro.2018.08.177

Ge, Q., He, T., Xiong, F., Zhao, P., Lu, Y., Liu, Y., & Zhou, N. (2020). Performance study of SC wall based on experiment and parametric analysis. *Journal of Civil Engineering and Management*, *26*(3), 227–246. https://doi.org/10.3846/jcem.2020.12181

Han, Y., Liang, M., Easa, S. M., Tang, W., Chu, P., & Gao, X. (2019). Optimal hydraulic section of horizontal-bottom catenary channel. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, *35*(6), 90–99.

He, Z. Q., Zhuo, W., Jiang, Y., Zhang, S., Liu, Z., & Ma, Z. J. (2020). Transverse post-tensioning in long-span concrete box-girder bridges: Refined modeling and alternative system. *Journal of Bridge Engineering*, *25*(3), 04020005. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001528

Helmers, E., Chang, C. C., & Dauwels, J. (2021). Carbon footprinting of universities worldwide: Part I—objective comparison by standardized metrics. *Environmental Sciences Europe*, *33*(1), 30. https://doi.org/10.1186/s12302-021-00454-6

Huang, C., Song, J., Zhang, N., & Lee, G.C. (2019). Seismic performance of precast prestressed concrete bridge girders using field-cast ultrahigh-performance concrete connections. *Journal of Bridge Engineering*, *24*(6), 04019046. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001416

Jiang, Y., Asante, D., Zhang, J., & Cao, M. (2020). The effects of environmental factors on low-carbon innovation strategy: A study of the executive environmental leadership in China. *Journal of Cleaner Production*, *266*, 121998. https://doi.org/10.1016/j.jclepro.2020.121998

King, A. W., Andres, R. J., Davis, K. J., Hafer, M., Hayes, D. J., Huntzinger, D. N., de Jong, B., Kurz, W. A., McGuire, A. D., Vargas, R., Wei, Y., West, T. O., & Woodall, C. W. (2015). North America's net terrestrial CO_2 exchange with the atmosphere 1990–2009. *Biogeosciences*, *12*(2), 399–414. https://doi.org/10.5194/bg-12-399-2015

Kunc, M. (2018). External environment: Political, economic, societal, technological and environmental factors. In M. Kund (Ed.), *Strategic analytics: Integrating management science and strategy* (pp. 55–78). Wiley. https://doi.org/10.1002/9781119519638.CH3

Li, Y., Li, P., Li, Y., Feng, J., Liu, Y., Yan, Z., Liu, Y., Gui, Y., & Yang, Z. (2020). Research on key technologies of construction management of large Swivel bridge based on BIM technology – A case study of Dade Swivel Bridge. *IOP Conference Series: Earth and Environmental Science*, *568*, 012052. https://doi.org/10.1088/1755-1315/568/1/012052

Le Quéré, C., Peters, G. P., Andres, R. J., Andrew, R. M., Boden, T. A., Ciais, P., Friedlingstein, P., Houghton, R.A., Marland, G., Moriarty, R., Sitch, S., Tans, P., Arneth A., Arvanitis, A., Bakker, D. C. E., Bopp, L., Canadell, J. G., Chini, L. P., Doney, S. C., ... Zaehle, S. (2014). Global carbon budget 2013. *Earth System Science Data*, *6*(1), 235–263. https://doi.org/10.5194/essd-6-235-2014

Molina-Moreno, F., Martí, J. V., & Yepes, V. (2017). Carbon embodied optimization for buttressed earth-retaining walls: Implications for low-carbon conceptual designs. *Journal of Cleaner Production*, *164*, 872–884. https://doi.org/10.1016/j.jclepro.2017.06.246

Moussavi Nadoushani, Z. S., & Akbarnezhad, A. (2015). Effects of structural system on the life cycle carbon footprint of buildings. *Energy and Buildings*, *102*, 337–346. https://doi.org/10.1016/j.enbuild.2015.05.044

Nam, K.-M., Waugh, C. J., Paltsev, S., Reilly, J. M., & Karplus, V. J. (2013). Carbon co-benefits of tighter SO_2 and NO_x regulations in China. *Global Environmental Change*, *23*(6), 1648–1661. https://doi.org/10.1016/j.gloenvcha.2013.09.003

Nemeth, C. P., & Herrera, I. (2015). Building change: Resilience engineering after ten years. *Reliability Engineering and System Safety*, *141*, 1–4. https://doi.org/10.1016/j.ress.2015.04.006

Othuman Mydin, M. A., Sani, N. M., & Phius, A. F. (2014). Investigation of industrialised building system performance in comparison to conventional construction method. *MATEC Web of Conferences*, *10*, 04001. https://doi.org/10.1051/matecconf/20141004001

Penadés-Plà, V., García-Segura, T., Martí, J. V., & Yepes, V. (2018). An optimization-LCA of a prestressed concrete precast bridge. *Sustainability*, *10*(3), 685. https://doi.org/10.3390/su10030685

Pons, J. J., Penadés-Plà, V., Yepes, V., & Martí, J. V. (2018). Life cycle assessment of earth-retaining walls: An environmental comparison. *Journal of Cleaner Production*, *192*, 411–420. https://doi.org/10.1016/j.jclepro.2018.04.268

Rinke, M. (2018). From structural performance to performative structures: New narratives in footbridge design. *Structural Engineering International*, *28*(4),408–417. https://doi.org/10.1080/10168664.2018.1477481

Ruparathna, R., Hewage, K., & Sadiq, R. (2016). Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, *53*, 1032–1045. https://doi.org/10.1016/j.rser.2015.09.084

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B. H., Apps, M. J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A. S., Field, C. B., et al. (2001). Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature*, 414, 169–172. https://doi.org/10.1038/35102500

Srivastava, M., Gopalakrishnan Narayanamurthy, Moser, R., Pereira, V., & Paille, P. (2021). Supplier's response to institutional pressure in uncertain environment: Implications for cleaner production. *Journal of Cleaner Production*, *286*, 124954. https://doi.org/10.1016/j.jclepro.2020.124954

Suhendro, B. (2014). Toward green concrete for better sustainable environment. *Procedia Engineering*, *95*, 305–320. https://doi.org/10.1016/j.proeng.2014.12.190

Tchidi, M. F., He, Z., & Li, Y. B. (2012). Process and quality improvement using six sigma in construction industry. *Journal of Civil Engineering and Management*, *18*(2), 158–172. https://doi.org/10.3846/13923730.2012.657411

Teng, Y., Mao, C., Liu, G., & Wang, X. (2017). Analysis of stakeholder relationships in the industry chain of industrialized building in China. *Journal of Cleaner Production*, *152*, 387–398. https://doi.org/10.1016/j.jclepro.2017.03.094

Vincenzi, S. L., Possan, E., de Andrade, D. F., Pituco, M. M., Santos, T. de O., & Jasse, E. P. (2018). Assessment of environmental sustainability perception through item response theory: A case study in Brazil. *Journal of Cleaner Production*, *170*, 1369–1386. https://doi.org/10.1016/j.jclepro.2017.09.217

Wang, T., Gao, S., Li, X., & Ning, X. (2018). A meta-network-based risk evaluation and control method for industrialized building construction projects. *Journal of Cleaner Production*, *205*, 552–564. https://doi.org/10.1016/j.jclepro.2018.09.127

Wuni, I. Y., Shen, G. Q. P., & Osei-Kyei, R. (2019). Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. *Energy and Buildings*, *190*, 69–85. https://doi.org/10.1016/j.enbuild.2019.02.010

Xu, F., Yu, H., & Zhang, M. (2019). Aerodynamic response of a bridge girder segment during lifting construction stage. *Journal of Bridge Engineering*, *24*(8), 05019009. https://doi.org/10.1061/(ASCE)BE.1943-5592.0001446

Yadav, N., Chatterjee, S., & Ganguly, A. R. (2020). Resilience of urban transport network-of-networks under intense flood hazards exacerbated by targeted attacks. *Scientific Reports*, *10*(1), 10350. https://doi.org/10.1038/s41598-020-66049-y

Yang, J., & Cheng, Q. (2020). The impact of organizational resilience on construction project success: Evidence from large-scale construction in China. *Journal of Civil Engineering and Management*, *26*(8), 775–788. https://doi.org/10.3846/jcem.2020.13796

Yang, Y., Zhang, S., Hou, H., & Chen, F. (2019). Resilience mechanism of land ecosystem in mining area based on nonlinear dynamic model. *Meitan Xuebao/Journal of the China Coal Society*, *44*(10), 3174–3184. https://doi.org/10.13225/j.cnki.jccs.2018.1272

Yepes, V., Martí, J. V., & García, J. (2020). Black hole algorithm for sustainable design of counterfort retaining walls. *Sustainability*, *12*(7), 2767. https://doi.org/10.3390/su12072767

Yoon, Y. C., Kim, K. H., Lee, S. H., & Yeo, D. (2018). Sustainable design for reinforced concrete columns through embodied energy and CO_2 emission optimization. *Energy and Buildings*, *174*, 44–53. https://doi.org/10.1016/j.enbuild.2018.06.013

Zhang, J., Long, Y., Lv, S., & Xiang, Y. (2016). BIM-enabled modular and industrialized construction in China. *Procedia Engineering*, *145*, 1456–1461. https://doi.org/10.1016/j.proeng.2016.04.183

Zhang, J., Li, W., & Yang, Z. (2020). Study on mechanical properties of wall panel with insulation decoration structure. *IOP Conference Series: Materials Science and Engineering*, *744*, 012036. https://doi.org/10.1088/1757-899X/744/1/012036

Zhou, W. (2021). Carbon emission estimation of prefabricated buildings based on Life Cycle Assessment model. *Nature Environment and Pollution Technology*, *20*(1), 147–152. https://doi.org/10.46488/NEPT.2021.V20I01.015

Zhou, Z., Alcalá, J., & Yepes, V. (2020a). Bridge carbon emissions and driving factors based on a Life-Cycle Assessment case study: Cable-stayed bridge over Hun He River in Liaoning, China. *International Journal of Environmental Research and Public Health*, *17*(16), 5953. https://doi.org/10.3390/ijerph17165953

Zhou, Z., Alcalá, J., & Yepes, V. (2020b). Environmental, economic and social impact assessment: Study of bridges in China's five major economic regions. *International Journal of Environmental Research and Public Health*, *18*(1), 122. https://doi.org/10.3390/ijerph18010122

Zhou, Z., Alcalá, J., Kripka, M., & Yepes, V. (2021a). Life Cycle Assessment of bridges using Bayesian networks and fuzzy mathematics. *Applied Sciences*, *11*(11), 4916. https://doi.org/10.3390/app11114916

Zhou, Z., Alcalá, J., & Yepes, V. (2021b). Optimized application of sustainable development strategy in international engineering project management. *Mathematics*, *9*(14), 1633. https://doi.org/10.3390/math9141633