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LIFE CYCLE OPTIMIZATION ANALYSIS OF BRIDGE SUSTAINABLE DEVELOPMENT

DOCTORAL THESIS

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UNIVERSITAT POLITÈCNICA DE VALÈNCIA

DOCTORAL TESIS

ANALISIS DE OPTIMIZACION DEL CICLO DE VIDA DEL DESARROLLO SOSTENIBLE DE UN PUENTE

Thesis submitted by

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Programa de Doctorado en Infraestructuras de Transporte y Territorio

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Pay tribute to my alma mater **UPV**; it is your broad mind and firm dedication that nurtured me now. I will always support you and follow you to the peak of science.

Pay tribute to **my colleagues** who have accompanied me through the ups and downs.

Pay tribute to **my family** and parents, always silently support your restless son, and come across the ocean to study.

Salute to my lifelong teacher, **Víctor Yepes Piqueras** and **Julián Alcalá González**; you have given me the second life of my study career and will accompany me to walk the rest of my body.

Finally, I pay tribute to **my wife**; it is you who dedicated your life to me, let me realize my dream, and love you all my life.

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After nearly four years (1226 days), I finally came to the day of graduation. All this is like a dream, although it is a nightmare to become a beautiful dream. My dear friends once asked me, what are you still struggling with now? Are you already middle-aged? After being silent for a long time, I do not know how to answer. I smiled and did not answer, unable to hide the long-lost desolation and pain in my heart. As of today, it still does!

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I wrote a few lines of poems to confirm my journey of study and my feelings after the test of time:

After leaving my family, wife, and children;
I crossed the ocean to Reino de España;
A new world, a new journey;
Study, the only way out;
To realize my dreams;
To pursue my world.
As Mr. Lu Xun said: Cherish loneliness, endure loneliness,
and often get surprises after loneliness.

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Finally, thank my parents, wife, son, and family. I traveled alone for four years. As the son of a father, husband of a wife, and father of a son who was studying on the other side of the globe. He abandoned their filial piety toward their parents, Love to his wife, and looked after his son. I never stepped into the home once in four years. The family members have encouraged and supported me from beginning to end and have given me years of care, understanding, and care. This deep love will permanently be engraved in my heart. Especially my wife, taking care of the older adult and the son of education, working hard all day and all night without a single complaint; this dedication and love will accompany me for the rest of my life!

I am sending heartfelt gratitude and sincere thanks again.

Abstract

At the heart of the global construction industry is the overuse of materials, especially non-renewable fossil energy raw materials. In this research direction, many researchers and designers have significantly reduced the proportion of materials and minimized the amount of design within the scope of research ideas and design specifications. Given whether the above measures can effectively reduce materials, several questions need to be further studied: a) In which stages of the life cycle of building materials are consumed more? b) How to use the most compelling scientific method to reduce the consumption of materials at the stage where materials are used the most? c) How to scientifically complete the material consumption optimization evaluation in the design stage under the influence of overcoming many discrete events and external influencing factors? d) In the construction stage, how to optimize the project management process to the greatest extent and achieve the most excellent material saving to ensure quality, safety and cost? e) How much material can be saved through design and project management optimization? f) What are the ultimate impact of the above research theoretical system and analysis data on the sustainable development of the construction industry?

Through the investigation of relevant publications on the whole life cycle of the construction industry (chapter 2), the thesis finds that the design and construction stages are the key to effectively reducing material consumption. The main goal of this thesis is to solve the proposed optimization problems. By establishing a multi-dimensional research model framework and a systematic project management optimization model, the thesis reduces the weight of various components of the statically indeterminate bridge structure and realizes the lightweight optimization of the bridge structure.

The thesis establishes several core theoretical innovation models in the research model framework: the bibliometric coupling model, ComplexPlot

mathematical model; the multi-factor integral mathematical model; the multi-dimensional finite element micro and macro coupling optimization model, and the entropy weight method domino project management optimization evaluation model. The theoretical research system overcomes the interference of the research object's discreteness, complexity, and uncertain influencing factors and realizes the robustness of evaluation and improvement. It comprehensively improves the model's resistance to natural, human, accidental, and uncertain factors and the external interference problem of emergencies. Ultimately, the system formed a complete set of mature joint prevention and control optimization model systems and realized the research goals and paradigms.

The case study proves the robustness of the established theoretical model system, which reduces LCC = 1,081,248.68 CNY; LCA = 212,566.94 t; SIA = 17,783,505.12 Mrh from the economic impact study analysis. Reducing LCC = 739,612.19 CNY; LCA = 278,455.12 t; SIA = 23,262,239.52 Mrh from sustainable development impact analysis. The questions raised by the study are well theoretically stated and strongly supported by the data.

The research value of this thesis: a) fills the research gap in this field. b) innovates a variety of new theoretical research models. c) solves the problems of discreteness, uncertainty, and external factor interference in topology optimization and project management optimization. Compensation and correction are made for the interference of external mutation factors and the sensitivity of emergencies. d) The research improves the Monte Carlo software analysis system's discrete data capture and compensation shortage.

In this thesis, various types of advanced project management methods and advanced construction schemes are applied in the case study, which provides a rich reference value for optimizing statically indeterminate bridges of the same type. For readers without extensive practical experience, there are some difficulties in understanding and applying the model. The reader needs to think carefully in combination with the case, which is also the insufficiency of this thesis.

The author's future research direction is to continue in-depth research on the sustainable development of super-large bridges and optimization of disease prevention, advanced materials, and renewable energy compensation research in the sustainable development of bridges and other fields.

Resumen

En el núcleo de la industria mundial de la construcción radica el uso excesivo de materiales, especialmente de combustibles fósiles. En esta línea de investigación, muchos investigadores y diseñadores han reducido significativamente la proporción de materiales y han minimizado la cantidad destinada al diseño en función de los criterios de investigación y las especificaciones de diseño. Teniendo en cuenta que las medidas anteriores pueden reducir los materiales de manera efectiva, es necesario investigar más a fondo algunas cuestiones: a) ¿En qué etapas del ciclo de vida de los materiales de construcción se consumen más? b) ¿Cómo utilizar el método científico más adecuado para reducir el consumo de materiales en la fase de mayor uso? c) ¿Cómo completar científicamente la evaluación de la optimización del consumo de materiales bajo la influencia de la superación de muchos eventos discretos y factores de influencia externos durante la etapa de diseño? d) En la fase de construcción, ¿cómo optimizar al máximo el proceso de gestión del proyecto y lograr el mayor ahorro de material para garantizar la calidad, la seguridad y el coste? e) ¿Cuánto material se puede ahorrar mediante la optimización del diseño y la gestión del proyecto? f) ¿Cuál es el impacto final del sistema teórico de investigación y de los datos de análisis mencionados en el desarrollo sostenible de la industria de la construcción?

Al examinar publicaciones relevantes sobre el ciclo de vida completo de la industria de la construcción (Capítulo 2), la tesis encontró que las etapas de diseño y construcción son clave para reducir efectivamente el consumo de materiales. El objetivo principal de esta tesis es resolver los problemas de optimización propuestos. Mediante el establecimiento de un marco de modelo de investigación multidimensional y un modelo de optimización de gestión de proyectos sistemático, la tesis reduce el peso de varios componentes

estructurales del puente estáticamente indeterminado y realiza la optimización ligera de la estructura del puente.

La tesis establece varios modelos teóricos básicos de innovación en el marco del modelo de investigación: el modelo de acoplamiento bibliométrico, el modelo matemático ComplexPlot; el modelo matemático integral multifactorial; el modelo de optimización de acoplamiento micro y macrodimensional de elementos finitos, y el modelo de evaluación de optimización de la gestión de proyectos dominó del método de la entropía. El sistema de investigación teórica supera la interferencia de la discreción del objeto de investigación, la complejidad y los factores de influencia inciertos y realiza la solidez de la evaluación y la mejora. El sistema de investigación teórica supera la interferencia de la discreción del objeto de investigación, la complejidad y los factores de influencia inciertos y consigue la solidez de la evaluación y la mejora. Asimismo, mejora ampliamente la resistencia del modelo a los factores naturales, humanos, accidentales e inciertos y el problema de la interferencia externa de las emergencias. Por último, el sistema formó un conjunto completo de sistemas de modelos de optimización de prevención y control conjuntos maduros y alcanzó los objetivos y enfoques de la investigación.

El estudio de caso demuestra la solidez del sistema del modelo teórico establecido, que reduce el coste del ciclo de vida (LCC) = 1.081.248,68 Chino yuan (CNY); Evaluación del ciclo de vida (LCA) = 212.566,94 tonelada (t); Evaluación del impacto social (SIA) = 17.783.505,12 hora de riesgo medio (Mrh) del análisis del estudio de impacto económico. Reducción del coste del ciclo de vida (LCC) = 739.612,19 Chino yuan (CNY); Evaluación del ciclo de vida (LCA) = 278.455,12 tonelada (t); Evaluación del impacto social (SIA) = 23.262.239,52 hora de riesgo medio (Mrh) del análisis del impacto en el desarrollo sostenible. Las preguntas formuladas en esta tesis están correctamente planteadas desde la perspectiva teórica y están fuertemente respaldadas por los datos.

El valor de la investigación de esta tesis: a) llena el vacío de la investigación en este campo. b) innova en una variedad de nuevos modelos teóricos de investigación. c) resuelve los problemas de discreción, incertidumbre e interferencia de factores externos en la optimización de la topología y la optimización de la gestión de proyectos. Las interferencias de los factores externos de mutación y la sensibilidad de las emergencias se compensan y corrigen. d) La investigación mejora la captura de datos discretos y la escasez de compensación del sistema de análisis de software Monte Carlo.

En esta tesis, se aplican varios tipos de métodos avanzados de gestión de proyectos y esquemas de construcción avanzados en el caso de estudio, lo que proporciona un importante valor de referencia para la optimización de puentes estáticamente indeterminados del mismo tipo. Hay algunas dificultades para los lectores sin una experiencia práctica para comprender y aplicar el modelo. El lector debe leer atentamente este caso, que es también una de las limitaciones de este trabajo.

La futura dirección de la investigación del autor es continuar investigando en profundidad el desarrollo sostenible de los puentes de gran tamaño y la optimización de la prevención de problemas, los materiales avanzados y la investigación de recuperación de energía renovable en el desarrollo sostenible de los puentes y otros campos.

Resum

En el nucli de la indústria mundial de la construcció radica l'ús excessiu de materials, especialment de combustibles fòssils. En aquesta línia d'investigació, molts investigadors i dissenyadors han reduït significativament la proporció de materials i han minimitzat la quantitat destinada al disseny en funció dels criteris d'investigació i les especificacions de disseny. Tenint en compte que les mesures anteriors poden reduir els materials de manera efectiva, és necessari investigar més a fons algunes qüestions: a) En quines etapes del cicle de vida dels materials de construcció es consumeixen més? b) Com utilitzar el mètode científic més adequat per a reduir el consum de materials en la fase de major ús? c) Com completar científicament l'avaluació de l'optimització del consum de materials sota la influència de la superació de molts esdeveniments discrets i factors d'influència externs durant l'etapa de disseny? d) En la fase de construcció, com optimitzar al màxim el procés de gestió del projecte i aconseguir el major estalvi de material per a garantir la qualitat, la seguretat i el cost? e) Quant material es pot estalviar mitjançant l'optimització del disseny i la gestió del projecte? f) Quin és l'impacte final del sistema teòric d'investigació i de les dades d'anàlisis esmentades en el desenvolupament sostenible de la indústria de la construcció?

En examinar publicacions rellevants sobre el cicle de vida complet de la indústria de la construcció (Capítol 2), la tesi va trobar que les etapes de disseny i construcció són clau per a reduir efectivament el consum de materials. L'objectiu principal d'aquesta tesi és resoldre els problemes d'optimització proposats. Mitjançant l'establiment d'un marc de model d'investigació multidimensional i un model d'optimització de gestió de projectes sistemàtic, la tesi redueix el pes de diversos components estructurals del pont estàticament indeterminat i realitza l'optimització lleugera de l'estructura del pont.

La tesi estableix diversos models teòrics bàsics d'innovació en el marc del model d'investigació: el model d'acoblament bibliomètric, el model matemàtic

ComplexPlot; el model matemàtic integral multifactorial; el model d'optimització d'acoblament micro i macrodimensional d'elements finits, i el model d'avaluació d'optimització de la gestió de projectes va dominar del mètode de l'entropia. El sistema d'investigació teòrica supera la interferència de la discreció de l'objecte d'investigació, la complexitat i els factors d'influència incerts i realitza la solidesa de l'avaluació i la millora. El sistema d'investigació teòrica supera la interferència de la discreció de l'objecte d'investigació, la complexitat i els factors d'influència incerts i aconsegueix la solidesa de l'avaluació i la millora. Així mateix, millora àmpliament la resistència del model als factors naturals, humans, accidentals i incerts i el problema de la interferència externa de les emergències. Finalment, el sistema va formar un conjunt complet de sistemes de models d'optimització de prevenció i control conjunts madurs i va aconseguir els objectius i enfocaments de la investigació.

L'estudi de cas demostra la solidesa del sistema del model teòric establit, que redueix el cost del cicle de vida (LCC) = 1.081.248,68 Xinés iuan (CNY); Avaluació del cicle de vida (LCA) = 212.566,94 tona (t); Avaluació de l'impacte social (SIA) = 17.783.505,12 hora de risc mitjà (Mrh) de l'anàlisi de l'estudi d'impacte econòmic. Reducció del cost del cicle de vida (LCC) = 739.612,19 Xinés iuan (CNY); Avaluació del cicle de vida (LCA) = 278.455,12 tona (t); Avaluació de l'impacte social (SIA) = 23.262.239,52 hora de risc mitjà (Mrh) de l'anàlisi de l'impacte en el desenvolupament sostenible. Les preguntes formulades en aquesta tesi estan correctament plantejades des de la perspectiva teòrica i estan fortament recolzades per les dades.

El valor de la investigació d'aquesta tesi: a) ompli el buit de la investigació en aquest camp. b) innova en una varietat de nous models teòrics d'investigació. c) resol els problemes de discreció, incertesa i interferència de factors externs en l'optimització de la topologia i l'optimització de la gestió de projectes. Les interferències dels factors externs de mutació i la sensibilitat de les emergències es compensen i corregeixen. d) La investigació millora la captura de dades discretes i l'escassetat de compensació del sistema d'anàlisi de programari Muntanya Carlo.

En aquesta tesi, s'apliquen diversos tipus de mètodes avançats de gestió de projectes i esquemes de construcció avançats en el cas d'estudi, la qual cosa proporciona un important valor de referència per a l'optimització de ponts estàticament indeterminats del mateix tipus. Hi ha algunes dificultats per als lectors sense una experiència pràctica per a comprendre i aplicar el model. El lector ha de llegir atentament aquest cas, que és també una de les limitacions d'aquest treball.

La futura direcció de la investigació de l'autor és continuar investigant en profunditat el desenvolupament sostenible dels ponts de gran grandària i l'optimització de la prevenció de problemes, els materials avançats i la investigació de recuperació d'energia renovable en el desenvolupament sostenible dels ponts i altres camps.

Table of contents

List of figures

List of tables

Full-text abbreviations

Number	Abbreviation	Full name
1	CE	Carbon emissions
2	3D	Three dimensional
3	SD	Sustainable development
4	CSB	Cable-stayed bridge
5	LCA	Life cycle assessment Evaluación del ciclo de vida (Español)
6	LCC	Life cycle costing Coste del ciclo de vida (Español)
7	SIA	Social impact assessment Evaluación del impacto social (Español)
8	ISO	International organization for standardization
9	WoS	Web of science
10	SCB	Strongest citation bursts
11	Eq\Eqs	Equation\Equations
12	SSE	The sum of squares due to error
13	R-squre	Coefficient of determination
14	MM	Maintenance and management
15	CNY	China yuan Chino yuan (Español)
16	TO	Topology optimization
17	EO	Ecologically optimization
18	EPC	Engineering procurement construction
19	JMB	Jin Ma bridge

20	VI	Visual identity
21	GDP	Gross domestic product
22	Gt	Gigatons
23	CO_2	Carbon dioxide
24	LCIA	Life cycle impact assessment
25	LCCA	Life cycle cost assessment
26	SILA	Social impact life assessment
27	Q	Network clustering module index
28	QS	Modularity index
29	LCI	Life cycle checklist
30	LLR	The keyword label
31	t	Ton\Tonnes Tonelada (Español)
32	Mrh	Med risk hours Hora de riesgo medio (Español)
33	PMO	Project management optimization
34	SA	Sustainable assessment
35	SETAC	Society of environmental toxicology and chemistry
36	UNEP	United nations environment programme

Chapter 1. Introduction

Highway bridges are an essential part of regional network traffic and a vital element of cross-regional traffic systems in all countries worldwide. Because the operation efficiency of the traffic system has a significant impact on the primary input and output of economies, an efficient and developed transport system can reduce the cost of everything in the economy and enrich the living standard of modern society, which is called agglomeration economies (Winston, 2013). This is mainly reflected in the improvement in employment rate, the rapid development of the consumer service industry, the cross-regional competition of enterprises, and the interconnected growth of economies. From 1995 to 2013, European countries invested EUR 66 billion in road construction. States and federal governments of the United States spent USD 2.4 trillion on transport, accounting for 17% of GDP in that year, and the traffic capital stock reached USD 4 trillion (2009). Expressway has become the pillar of speeding up the cross-border and cross-regional transport of products, materials, and passengers evolved into a catalyst for economic and social development (Radzi et al., 2021). From 2010 to 2020, the total output value of China's construction industry was USD 7,966.41 billion, accounting for 7.65% of the GDP on average, and that of the transport industry is USD 4,985.52 billion, accounting for 4.44% of GDP on average (calculated according to the average exchange rate of 6.9 in 2020) (Li et al., 2016; Gao et al., 2018).

Due to the speedy urbanization and economic growth in major regions of the world, there are higher requirements for the quantity and quality of transport infrastructure. A practical and well-designed traffic system can promote the rapid growth of trade and economy and reduce product costs the scale and integration of the market economy, and the competitive trade advantage to ensure high returns for countries and enterprises (Mohmand et al., 2021). In this context, designers face comprehensive challenges: under the conditions of structural safety and economy, designers should consider improving of the beauty, service life, and higher traffic capacity of the facilities while developing innovation schemes (Cheung et al., 2000). The optimal design has become the synthetic art of solving technical issues with scientific methods, aiming to realize harmony between man and nature, the perfection of economy and safety, minimization of pollution, and resources and so on (Sobrino, 2021).

Chao Zhang et al. (2011) Strategies for promoting sustainable networks on UK roads and rail are described: a) Reduce rework; b) Improve on-site productivity; c) Effectively manage supply chain; d) Utilize new materials, products, and technologie. The primary professional qualities and work requirements for professionals related to bridge sustainability are as follows:

Scientific research personnel: a) Carry out environmental impact analysis for specific types of bridge engineering; b) Quantize CE from real bridge projects; c) Design and maintain interactive environment and economic benefits; d) Conduct application-oriented research and develop the best guidelines; e) Develop a business case for sustainable bridge delivery (C. Zhang, 2010; Chao Zhang et al., 2011).

Design personnel: design is a fixed flexible system, which can survive, adapt and develop through the flexible approach to uncertain and unpredictable destruction, and its balance of adaptability is emphasized by ecological robustness, whose combination is the essential requirement of the design (Frank & Zeitouni, 2008). Oxford Institute for Sustainability has proposed the overall design method and framework guidelines for social, economic, and ecological dimensions: a) The starting point of sustainable design strategy is the existing challenges. b) The participation of users and stakeholders is the essential attribute of design solutions to the meaningful, sustainable products. c) Promoting interdisciplinary experiences, including providing comprehensive learning opportunities for different stakeholders is very important (theory, practice, and poetry) (Keitsch, 2012).

Scientific researchers and builders put forward twelve principles of green engineering: a) Builders and structural engineers should ensure that the raw materials are low-carbon and pollution-free. b) Prevent or reduce waste formation at an early stage. c) Reduce the amount of energy and materials in the design separation and purification operations. d) Products and systems should maximize product quality, space, and practicability. e) Increase the effectiveness of products and systems through energy and material "output pulls." f) Use embedded entropy for investment design post-design process. g) Build durability design thinking and purpose. h) Avoid design flaws in capacity or efficiency design. i) Adopt the idea of dismantling and value preservation to reduce the diversity of multi-component materials. j) Design systems and products with integrated and interconnected design concepts. k) Focus on the design process's commercial regeneration value of systems and products. l) Focus on renewable design for materials and energy (Anastas & Zimmerman, 2003).

Construction personnel: they are the key to realizing more affordable, sustainable, easy construction and economy of the bridge: a) Directly save life cycle cost. b) Increase structural design and service life. c) Improve the excellent durability of components and reduce maintenance. d) Reduce the overall construction time and risk. e) Reduce the consumption of raw materials and adopt lighter superstructure and smaller substructure. f) Reduce human resources and machines, shorten the temporary construction period and reduce the impact on the construction site. g) Adopt reasonable construction methods, optimize the quality and improve the structural performance (Voo et al., 2015).

Maintenance personnel: maintain the sufficient function and safety level of the bridge structure, collect quality inspection data and carry out accurate condition evaluation and rating to determine the bridge maintenance, repair, and replacement. There are three parts for bridge assessment and care: deck, superstructure, and substructure (Alsharqawi et al., 2020).

The above is not only a paradigm standard for all participants in bridge sustainability but also an effective measure to ensure long-term SD and adapt to the rapidly changing social ecosystem. It is also the ideological and theoretical basis and driving source of this thesis research.

1.1. Research background

From the above simple analysis of the primary conditions of the construction and transportation industry in the whole life cycle (see 2.1 for the detailed analysis). It can be found that the large consumption of construction materials and the operation of the industrial chain of this industry are bound to emit a large number of greenhouse gases and environmental pollution. In particular, the rapid expansion of urbanization and global economic integration has worsened matters for researchers in this field. To optimize the number of materials, minimize and reduce the number of materials, and break through the constraints of structural redundancy performance to ensure the engineering structure's quality, progress, and safety.

Constrained by industry norms and laws and regulations, economic interests, and lack of innovative theoretical support, designers follow the conservative design of large-scale bridge structures, releasing a part of redundant structures and discrete factors to distribute in secondary components. Much literature published worldwide (see 2.2 for detailed analysis) has studied the content of sustainable bridge optimization, in which new and unique materials are used to replace standard components. Alternatively, some admixtures and catalysts are added to improve the durability and strength of primary materials, Extend component life, and maintain intervals. However, the fundamental problem of bridge structure optimization was not solved in the end: reducing the number of available materials, concrete and steel bars; bridge solid structure research provides designers with sufficient theoretical and practical value and visualizes the entire process of structural optimization, which genuinely allows investors, Government agencies and builders recognize the practical value of bridge structure topology optimization through simple models and methods and strive to be fully promoted and applied in fundamental engineering and building regulations.

The current research theoretical model system lacks the comprehensive optimization of the super bridge in the whole life cycle of the entity research. Most of the research focuses on a single component or part of the component. It uses shell elements, plate elements, and rod structures to replace them in modeling and simulating solid bridges. The finite element coupling change data of each grid element cannot be captured in the final miss stress analysis. The numerical model and analysis concluded that the research conclusion is replaced by the large and the small and the partial belt are full. Demonstrate the robustness of network lattice entities.

For the analysis and processing process of discrete influencing factors, as a scientific researcher. The structure's service in the natural environment is disturbed by many uncertain factors, such as an abusive environment, the stability of the structure itself, the dynamic characteristics of external loads, Fatigue effects of materials, Etc. How to solve the above problems? It is necessary to establish multiple representative theoretical models to improve the research's robustness and determine the final paradigm model.

At present, there are confusion and a lack of dealing with the influence of external uncertain interference factors in managing large-scale bridge projects about methods. The management focuses on controlling the progress and economic costs and failing to establish a proper planning and management system for crucial routes. The overall progress on the critical path cannot be accurately assessed and controlled in advance. The management relies on years of management experience to blindly advance the construction progress, lacking scientific planning and theoretical model analysis. The prior control system is not established or is not perfect, resulting in loopholes in the final project management model.

The core background of the research of this thesis is summarized above. Finally, the robustness of the theoretical framework of research innovation is proved through case studies, and the ultimate goal of sustainable development of large bridges is achieved.

1.2. Aims and contributions

The research idea model is determined (Figure 1.1), The five stages of bridge engineering are the key to the whole life cycle. Each stage involves many influencing factors and industries, the root cause of carbon emission, and social impact. The ultimate goal of the sustainable building strategy can be met under the conditions of meeting all technical and quality requirements achieving the lowest cost and the shortest construction period, and minimizing any adverse impact on the environment and the community (Chiang et al., 2014).

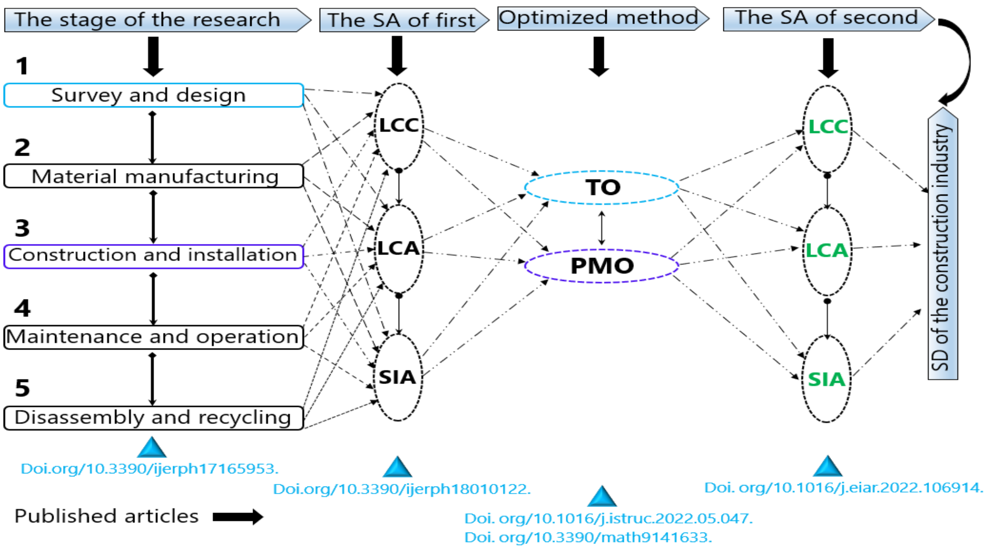


Figure 1.1. Model of research ideas.

Sources: Own elaboration.

In terms of reducing the sustainable impact of bridge structures, the key is to reduce the material consumption and the number of human resources, machines, and auxiliary materials (i.e., production, transportation, and construction). From the sustainable design perspective, the optimal design and analysis are carried out for the components, and the most economical section is obtained after optimizing the section area and reinforcement ratio (Yoon et al., 2018). Project management and technology are two key factors affecting the construction industry. The construction project management is characterized by long process duration, many uncertain influencing factors and risks, irreversibility, potential adverse effects, and uncertainties. The experience, education, team management ability, and value system of project managers directly affect the SD of the construction industry (Bröchner, 2021).

This thesis will design the optimal project management model from the aspects of project management teams' outlook on life, values, management experience, optimal management planning, and emotional quotient to achieve the SD goal of project management.

1.2.1. Questions of the research

The conceptual framework of SD consists of three pillars (LCC, LCA and SIA). The practice of the 21st century also includes the benefit of human development, humanized SD policies, sustainable spatial planning regulations, and sustainable engineering education (Takala & Korhonen-Yrjänheikki, 2019). This thesis focuses on the three pillars of bridge SD, aiming to achieve the goal of SD of the construction industry by analyzing the influencing and restrictive factors in the whole life cycle and implementing optimization strategies for each stage.

Conclusions of the literature review:

a) Through the data analysis of the top ten countries in terms of global carbon emissions, it is revealed that urbanization, infrastructure construction, and energy consumption are the main driving forces for ecological pollution.

b) Through the analysis of the carbon emission data in the construction industry of the top eleven countries, it is concluded that the carbon emission of the global construction industry is still in a stage of continuous growth (-5.49%~9.11%). Therefore, reducing carbon emissions in the construction industry remains a daunting task.

c) Through literature survey, bibliometric visualization methods, and three-dimensional polynomial fitting analysis of data. It is revealed that the core influencing factors of the three pillars (LCC, LCA, and SIA) of sustainable development of the construction industry in the whole life cycle are non-renewable energy and materials. consumed.

d) Through literature evaluation and analysis, five main aspects affecting the sustainable development of the construction industry are obtained: participants; machinery and equipment, transportation methods; building materials, and project management modes.

Through a discussion of the findings of the global literature survey and analysis, this section comprehensibly presents the core questions (**e** and **f**) that need to be analyzed and addressed in this thesis:

e) The most effective way to reduce and control the amount of material used in the project design phase - is the design method through structural optimization effective (within the interval that meets the design specification)?

e-1) Use multidisciplinary and interdisciplinary knowledge to analyze the structure's ultimate bearing capacity and structural redundancy under the most unfavorable load combination.

e-2) Given the acute effects of uncertain factors, random events (natural and human environment), aging, and structural wear on the sustainable development of bridges in the project evaluation process, it is crucial to establish an effective control evaluation model.

e-3) The method of maximizing the savings in material consumption in the bridge design phase - through the coupled analysis of the multi-dimensional finite element coupled 3D model to achieve the completion is challenging.

e-3-1) Through the establishment of various mathematical research models, the deficiencies in the analysis of the influence of Monte Carlo simulation on discrete data in the software are solved, and the robustness of the theoretical system of bridge sustainability evaluation is improved.

e-3-2) Based on the Lagrange multiplier rule and Weierstrass theorem, the multi-level maximum coupling optimization model of linear and nonlinear structures is derived, and the multi-dimensional topology optimization coupling theory system is established.

e-3-3) Breaking through the blank that large-scale statically indeterminate bridge structures cannot be divided into solid finite element meshes. Through the precise division of 350,109 single crystal meshes, the 3D finite element coupling model assembly and module visualization research are realized.

e-3-4) Through the established multi-dimensional 3D finite element coupled topology frame model, the optimal design of the material consumption of the structural components is completed, and the optimal design goal of structural material compensation is achieved.

f) In the project construction stage, the consumption of personnel, machinery, materials, and transportation is reduced by optimizing the project management mode to achieve the goal of sustainable optimization of management design.

f-1) Firstly, the multi-level interference factors of project management and the influence factors of discretized structure framework are analyzed. The critical influencing parameters of project management were identified.

f-2) Through analyzing 48 influencing factors in the vertical and horizontal three dimensions (cost, quality, and progress) of project management, a network system of vertical and horizontal interweaving and collaborative evaluation was established, and the discrete and diverse influencing factors were coordinated. Control.

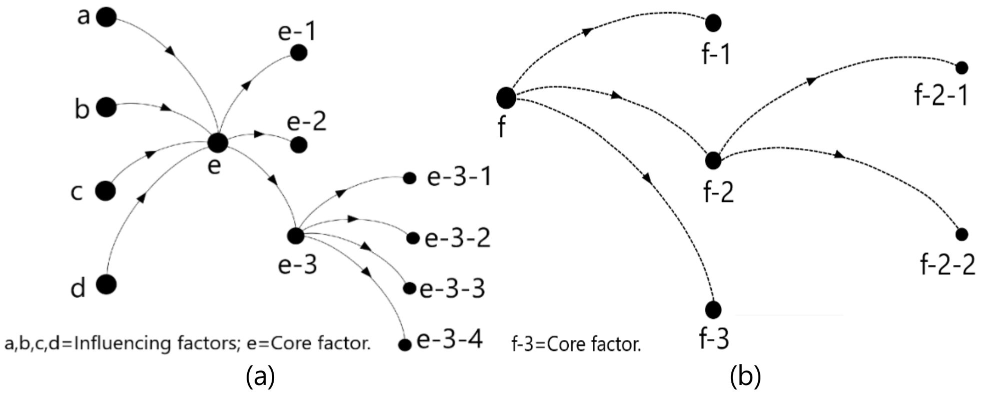


Figure 1.2. Network Visual Analysis. (a) SA. (b) Project management model.

Sources: Own elaboration and anaiysis.

1.2.2. Results of the research

The concluding data of the research case in Chapter 5 effectively demonstrate the validity and robustness of the models established in Chapters 3 and 4. conclusion as below:

a) The core problem **e** proposed by the thesis has been effectively solved and proved by case: The multi-dimensional topological coupling optimization study reduces the material consumption of JMB's design structure by 164.23 m^3. Equivalent to reducing LCC cost by 220,461.56CNY, reducing LCA emissions by 12,110.37 t, and SIA by 1,115,140.00 Mrh.

b) The core problem **f** proposed by the thesis has been effectively solved, and it is proved by the case that:

b-1) According to the project management optimization scheme 1. The analysis data showed that the reduction of LCC = 519,150.63CNY. LCA reduced emissions by 266,344.75 t, accounting for 1.405% of the designed initial emissions. SIA reduces emissions by 22,147,099.52 Mrh, accounting for 0.679% of the original design emissions.

b-2) According to the project management optimization scheme II. The analysis data showed that the reduction of LCC = 860,787.12CNY. LCA reduced emissions by 200,456.57 t, accounting for 1.057% of the total original emissions. SIA reduced emissions by 16,668,365.12 Mrh, accounting for 0.511%.

This thesis's final optimization design conclusion selects the (a)+(b-2) scheme: reduce the design economic cost LCC = 1,081,248.68CNY; reduce the LCA emission by 212566.94t; reduce the SIA emission by 17783505.12Mrh.

1.2.3. Contributions of the research

The contributions in this research are as follows:

a) Based on the analysis of global sustainability impact data using the multi-factor integral mathematical model, this thesis studies the research literature of six continents in 30 years by using citespace software and evaluates the research development trend and prospects. ComplexPlot mathematical analysis model is used to analyze the impact data of each continent based on color bandwidth, color difference, and color frequency and display the data vividly and flexibly. So far, this research method is blank.

b) For the sustainability research of bridge engineering in the construction industry, a system model is established. The change of influencing factors in any stage will drive the evolution of the whole research system (the model is named the domino evaluation model based on the entropy weight method).

c) For global universality, the latest and most mature system research framework (*ISO14--001~5*), perfect research software (OpenLCA1.10.1, OpenLCA1.10.3) and robust database (Ecoinvent, Bedec, Product Social Impact LCA) are used to research the bridge sustainability (ZhiWu Zhou et al., 2020b). Given the complexity of SD influencing factors, the multi-level planning influence model is innovated to mark the classification and show the new theoretical model.

d) The bridge structure is optimized, and the material consumption is reduced through comprehensive evaluation and analysis at each stage. The project management model is optimized according to the established best international project management model (Zhiwu Zhou et al., 2021) to achieve minimum emissions and sustainability.

e) The research cases selected are exceptional, novel, and representative. The case study sets the CSB, a structural system jointly loaded by tower, girder, and cable, for analysis. Topology optimization improve the robustness of the theoretical model, the cases with different structural forms (box girder and T-beam composite super central bridge) are selected. A 3D project management model is designed according to 3D entity structure design and sustainability analysis. Such research is blank in the existing literature (analyzed in Chapter Ⅳ).

f) Topology optimization study the innovation of mathematical model. A new multi-target optimized mathematical model and domino evaluation model based on the entropy weight method is created to find a remedy for the diversity and confusion of influencing factors, which is well proven in the case analysis.

1.3. Research methodology

The research methodology of this thesis is divided into five parts: LCC, LCA, SIA, 3D topology optimization and Mangement (Table 1.1, Chapters 2 and 3).

LCC: LCC is used as a research model for the total life cycle cost of the construction industry from the "cradle-grave," including the total cost from the early stage of planning to demolition. *ISO 15686-5*: *2008* buildings and constructed assets-service-life planning-part 5: Life-cycle costing. It provides guidelines for LCC analysis on buildings and construction assets and their components (Chen et al., 2005). Due to the complexity and high uncertainty of building structure, various countries have formulated their assessment methods and laws & regulations based on the overall framework. The basic parameters include investment, service, maintenance, and other costs related to taxes, insurance, disposal, residual value, Etc. (Petrović et al., 2021). Due to the particularity of the construction industry, there are discrete incidents of accidental damage, and a discrete cost assessment is added (see 3.1 for detailed theory).

LCA: This thesis's research method and framework are implemented according to *ISO 14040:2006* Environmental management-LCA-Principles and framework. *ISO 14040: 2006* covers the research on LCA and LCI (Finkbeiner et al., 2006). *ISO 14040*: *2006/AMD 1:2020*, published in September 2020, has made a revision and supplement based on the original framework and made some routine adjustments and improvements according to the global development to make the theoretical framework system more scientific and paradigm. In this thesis, the sensitivity evaluation of material loss rate, aging rate, recovery rate, and carbonization performance has been added to the five-stage model, improving the research model's functional performance and reliability. (see 3.2 for detailed theory).

SIA: In 1999, WACF incorporated social impact into the life cycle of the construction industry. In 2010, *ISO* provided a guide (*ISO26000: 2010*) to social responsibility, which stipulated that the sustainable business of the organization not only provides products and services satisfactory to customers but also does not harm the environment and operates in a socially responsible manner, and reduces damage to customers, governments, associations and the public. The guide is consistent with the labor standards established by the Ilo and has reached a consensus with oecd to ensure its consistency (ISO, 2010). The International Association for Impact Assessment (IAIA) has formulated the international guidelines and principles of SIA. This includes analyzing, monitoring, and managing anticipated and unintended social consequences of interventions (policies, programs, and projects) undertaken in previous planning and the social changes resulting from their implementation. Its purpose is to create a better, fair, and sustainable environment. Its framework focuses on feedback and subsequent assessment of how people and communities interact in their sociocultural, economic, and biophysical environments (Vanclay, 2003b). Because of the particularity of research cases and the influence of uncertain factors, the weighted aggregation method of index weights is added to evaluate category conclusion data to highlight the impact efficiency of different categories (see 3.3 for detailed theory).

Topology optimization and management: Through the analysis of the multi-material and multi-index 3D topology optimization theoretical system and model, the bridge topology optimization mathematical model is established according to the characteristics of linear and nonlinear materials, which meets the research requirements in the field of design and fixation. By analyzing the influencing factors of the project management model in different stages, the compensation elements of the project management model are established. A domino evaluation model based on the entropy weight method is proposed. The interference of uncertain factors and the influence of emergencies in multi-level management optimization are solved.

The task of this thesis is to realize sustainable bridge development, minimize the interference of labor, materials, machinery, equipment, and external environment through the optimization and innovation of the management model in each stage, realize the minimum cost, emission, and social impact, and establish the assessment paradigm of bridge SD. At the same time, the 3D finite element coupling optimization model is applied to realize the optimized lightweight structure and provide scientific support for saving raw materials and fossil energy. Moreover, provide the optimal line project management model, realize scientific management while realizing lightweight construction technology, and provides a paradigm for green and sustainable development (Table 1.1).

1.4. Dissertation structure

This thesis is divided into six chapters, the main contents are as follows:

Chapter I the research background, direction, contribution, main research methods, and some core application innovations of the thesis are introduced.

Chapter II to analyzes the status of carbon emissions and environmental pollution in six continents worldwide and the characteristics of the literature published by global researchers in this field. It further illustrates the importance, timeliness, and theoretical value of the research in this thesis.

Chapter III comprehensively describes the theoretical mathematical models of LCC, LCA, and SIA and makes a comparative study and analysis of the selection of model parameters.

Chapter IV introduces the theoretical model of bridge finite element optimization, and describes the establishment of the theoretical model of project management model.

Chapter V demonstrates the robustness of various theoretical model frameworks.

Chapter VI summarizes the conclusions and post-research plan.

1.5. Summary of this chapter

This chapter briefly introduces the research direction of this thesis, the source proof of research innovation, research methods and ideas, and the basic situation and framework so that readers can clearly understand the characteristics and research areas of this thesis (Figure 1.3).

Table 1.1. The core methodology of this thesis

CN	MC	Characteristics of innovative research methods	Methodological core
3.1.4	Establish LCC theory system	ISO15686-5 stipulates that LCC in the construction industry is the sum of costs incurred in different cycle stages, divided into costs of construction, service, occupation, maintenance, and end of life.	Maintenance and degradation models are established. Sensitivity effects on damage and maintenance costs are analyzed.
3.2.4	Establish LCA theory system	Established a complete assessment framework and modeling theory; project management mode and complex network mathematical model.	The impact of five uncertain factors on the model is addressed: inaccuracy, incompleteness, outdated or missing data, uncertainty in the model, and uncertainty caused by the research process.
3.3.4	Establish SIA theory system	Quantitatively analyze and identify multipath models with multiple impact categories to reduce and balance stakeholder interests and achieve SIA efficiencies. Effective mitigation plans have also been implemented to reduce negative social impacts.	A theoretical mathematical model based on the category indicators of the impact framework and considering the robustness of the impact weights.
4.1.3	Optimization method of system	A new evaluation framework to address the discreteness of weights and information and multi-criteria decision making to improve the sensitivity and stability of impact models in applications. Based on the discreteness and high coupling threshold of impact data, a new algorithm is studied and innovated to analyze linear and nonlinear optimization level solutions.	A Paradigm Model for Multi-level Planning Indicators Analysis Considering Sensitivity. The advantages of the solid isotropic material method with compensation, the homogenization method and the evolutionary structure optimization method are combined.

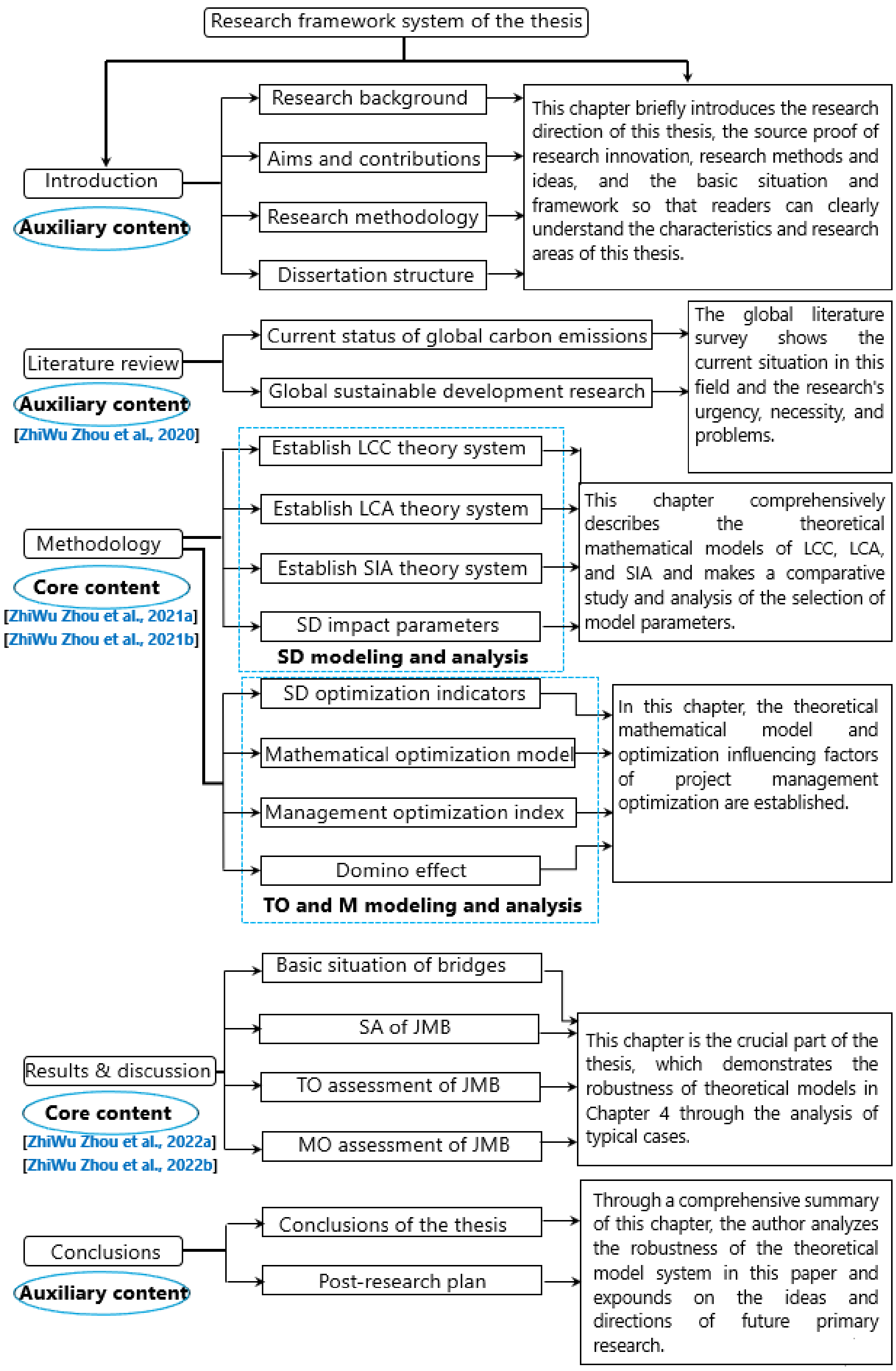
4.2.3	3D visualizati on innovatio n of bridge model	3D visualization innovation applies to the macro- and micro-structure of periodically structured multiphase materials. Composite materials consist of three-phase or multi-phase materials.	3D TO mathematical model
4.4.2	Domino evaluation model of entropy weight method	In view of the uncertainty and discreteness of the influencing factors of bridge engineering, a domino evaluation model based on entropy weight method is proposed.	The interference of uncertain factors and the influence of emergencies in multi-level management optimization are solved.

Notes: CN=Chapter number; MC=Method content.

Sources: Own elaboration.

Figure 1.3. The overall research process and model framework of this thesis.

Sources: Own elaboration and anaiysis.



Research framework system of the thesis
Introduction
Auxiliary content
Research background
Aims and contributions
Research methodology
Dissertation structure
This chapter briefly introduces the research direction of this thesis, the source proof of research innovation, research methods and ideas, and the basic situation and framework so that readers can clearly understand the characteristics and research areas of this thesis.
Literature review
Auxiliary content
[ZhiWu Zhou et al., 2020]
Current status of global carbon emissions
Global sustainable development research
The global literature survey shows the current situation in this field and the research's urgency, necessity, and problems.
Methodology
Core content
[ZhiWu Zhou et al., 2021a]
[ZhiWu Zhou et al., 2021b]
Establish LCC theory system
Establish LCA theory system
Establish SIA theory system
SD impact parameters
SD modeling and analysis
This chapter comprehensively describes the theoretical mathematical models of LCC, LCA, and SIA and makes a comparative study and analysis of the selection of model parameters.
SD optimization indicators
Mathematical optimization model
Management optimization index
Domino effect
TO and M modeling and analysis
In this chapter, the theoretical mathematical model and optimization influencing factors of project management optimization are established.
Results & discussion
Core content
[ZhiWu Zhou et al., 2022a]
[ZhiWu Zhou et al., 2022b]
Basic situation of bridges
SA of JMB
TO assessment of JMB
MO assessment of JMB
This chapter is the crucial part of the thesis, which demonstrates the robustness of theoretical models in Chapter 4 through the analysis of typical cases.
Conclusions
Auxiliary content
Conclusions of the thesis
Post-research plan
Through a comprehensive summary of this chapter, the author analyzes the robustness of the theoretical model system in this paper and expounds on the ideas and directions of future primary research.

Chapter 2. Literature review

This chapter is divided into three sections, which study the current situation of global carbon emission, the impact of the construction industry on global environmental pollution, the contribution of the scientific literature published by the six continents to this field, and the trend of research and development, and analyzes and infers the current situation of the six continents.

Through the research and data analysis in this section, the following questions are clarified:

a) The basic situation of carbon emissions in the world in 50 years (1970~2020) and the status quo of environmental governance in each country (the top 14 countries in GDP); a clear understanding through data analysis of 73.22% of the world's carbon emissions are concentrated in the top ten countries in terms of GDP.

b) The publications of research literature on sustainable development in six continents, the number of publications, the quality of the literature, and the deficiencies in this research field, and predict the critical directions of future research. It provides sufficient data support for the research value of this thesis.

c) A literature search in this field found that the evaluation system composed of bridge sustainable development coupling optimization and project management optimization is missing and needs to be supplemented and improved.

2.1. Current status of global carbon emissions

With the rapid urbanization, there are many issues, such as ecological fragmentation, weakened spatial system, water, and air pollution, heat island effect and reduced biodiversity, etc., seriously threatening sustainable urban development (C. Li et al., 2018).

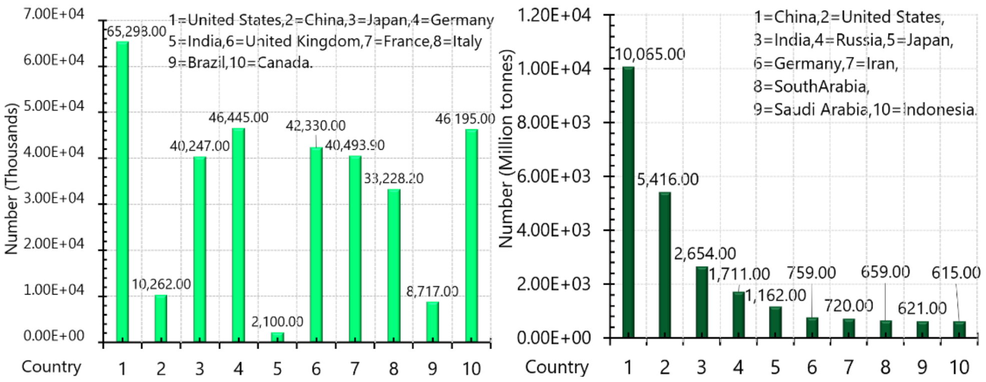
According to the data published by the United Nations Department of Economic and Social Affairs (UNDESA), in 2018, the world's urban population was 4.2 billion, accounting for 55% of the total population. It is expected to increase to 68% in 2050, including 416 million in India, 255 million in China, and 189 million in Nigeria, and the proportion of the world's urban population will increase by 35%. At present, the ratio of urban population (2018) is 82% in North America, 81% in Latin America and the Caribbean, 74% in Europe, 68% in Oceania, 50% in Asia, and 43% in Africa. The population of mega cities (2020) is 37 million in Tokyo, 29 million in New Delhi, 26 million in Shanghai, and 22 million in Mexico and Sao Paulo. It is estimated that there will be 43 megacities with more than 10 million in 2030 (Harris et al., 2019).

Internationally, green infrastructure is put forward for urbanization, and the urban ecological infrastructure can be promoted and improved through human settlement, environmental protection, and green technology. UN has put forward a series of agendas suitable for "sustainable cities and communities" to solve the contradiction of integrating between the natural environment and the architectural environment (Zheng & Barker, 2021). The UN was aiming how to reduce the ecological environment pollution of infrastructure, the UN has proposed to achieve the SD goal of reduction - reuse - recycling by reducing the excessive exploitation and transformation of natural resources at the source, effectively utilizing and designing the material consumption, extending the useful life, and improving the recovery and utilization of waste materials. In 2015, the European Commission put forward the policy of enhancing national competitiveness, reducing environmental pressure, improving resource efficiency and circular economy while strengthening "material forces of production" (Miatto et al., 2021). The control of *Architecture, Engineering & Construction (AEC)* is particularly crucial: The AEC industry is the world's largest consumer of raw materials. The carbon emission of the architectural environment accounts for 25~40% of the world. Sustainable infrastructure has become the key to national economic, social benefits, and environmental impact and has become the triple bottom line for countries to establish control indicators and system standards (B. Liu et al., 2021).

2.1.1. Current status of global carbon emissions

According to the comparison of the remaining two sets of data, the top five countries in the top ten countries in GDP also rank among the top six in CE. United Kingdom, France, Italy, Brazil, and Canada are not among the top ten in

CE, which have changed to Russia, Iran, South Arabia, Saudi Arabia, and Indonesia. Russia ranks 4th in carbon emission and 11th in GDP (Figure 2.1-b). In 2019, GDP was $87,345.3 billion. The total GDP of the top ten countries is USD 58,693.20 billion, accounting for 67.20% of the total. Global energy-related CO_2 emissions in 2019 at around 33.3 Gt. The total emission of the top ten countries is 24.38Gt, accounting for 73.22% of the global total (Figure 2.1-a).



(a) (b)

Notes: Source: (He et al., 2022; Ji & Chen, 2010); The top ten rankings of global GDP per capita (2019); Top ten countries in terms of global CE (2019).

Figure 2.1. Data comparison of the top ten countries in global GDP and CE (2019 year).

Sources: The data comes from (Ji & Chen, 2010).

The data analysis in Figure 2.1 shows that the rapid growth of GDP also has a significantly negative impact on the ecological environment, which has become the "only" fact recognized by scientific researchers. In addition, SD is also disturbed by many other factors, including GDP. Social well-being, economic progress, and environmental assessment are recognized as scientific standards for SD (Radovanović & Lior, 2017). Therefore, it is essential to study the historical CE. We can calculate the impact index of GDP on CE and environmental pollution through data analysis, showing the importance and practicability of this study. The per capita carbon emission of the top 14 countries (1980-2020) in GDP and total CE is selected for research and analysis (Ji & Chen, 2010).

The data analysis in Figure 2.2 shows that the per capita carbon emission of the United States ranks first in 41 years, with an average of 19.26 t/person, accounting for 15.97% of the total CE per capita of 14 countries. The difference

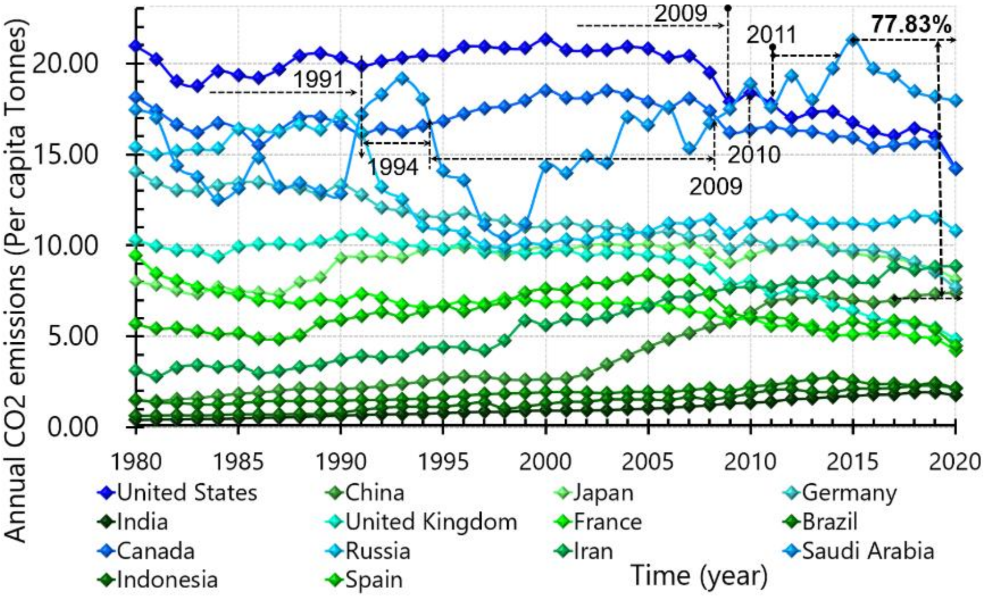


Figure 2.2. Data of the top 14 countries in global CE per capita.

Sources: The data comes from (Our World in Data, 2021).

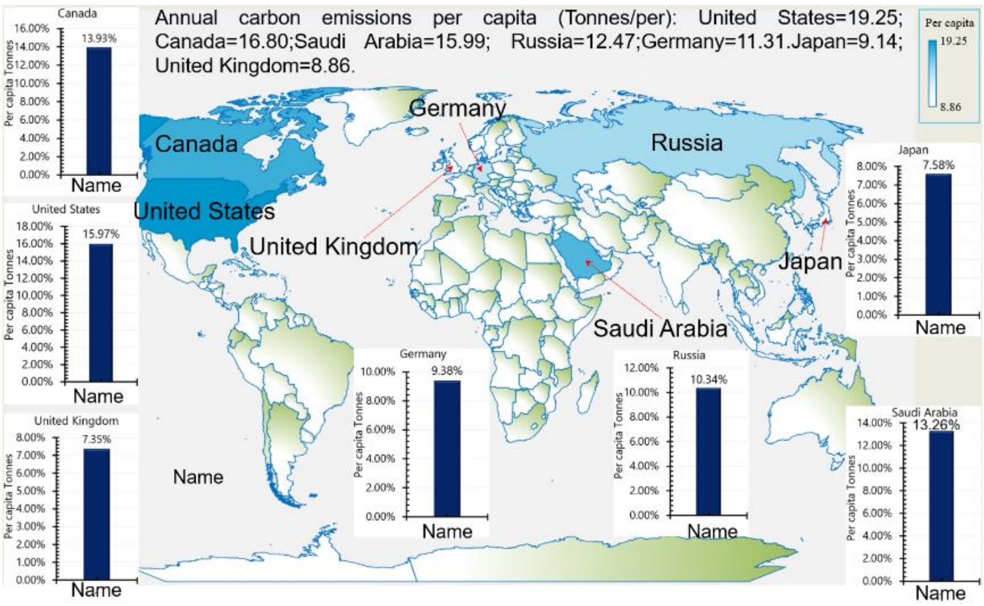
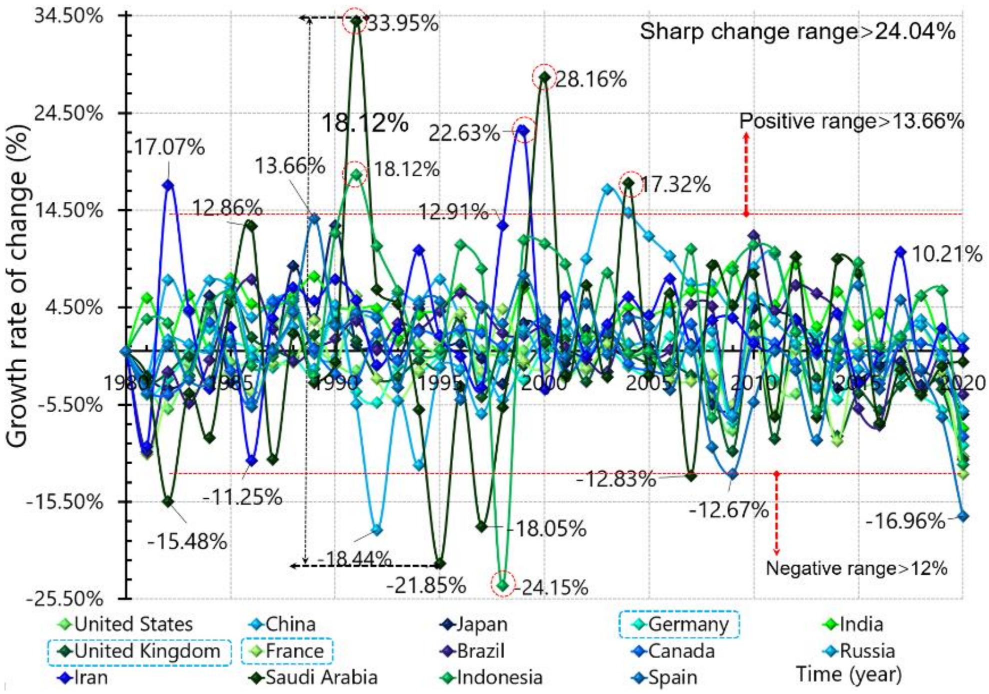


Figure 2.3. Time zone data for the top seven carbon-emitting countries.

Sources: Own elaboration and anaiysis.

between the data and the per capita total of the last six countries (among the 14 countries) is 0.92 t. The per capita carbon emission of the United States ranked first in the world from 1980 to 2009, which was 0.52 t/person in 2010, slightly lower than that of Saudi Arabia (ranked first from 2011 to 2020); Canada ranked second, with an average of 16.80 t/person, accounting for 13.93% of the total CE per capita; Saudi Arabia ranked third, with an average of 15.99 t/person, accounting for 13.26% of the total carbon emission per capita. Comparing the data of Canada and Saudi Arabia, it is found that: the per capita carbon emission of Canada from 1980 to 1991 was higher than that of Saudi Arabia, which was 2.59 t/person; the average value from 1991 to 1994 was less than 1.83 t/person; the per capita carbon emission of Canada from 1994 to 2009 was higher than that of Saudi Arabia, which was 3.42 t/person. From 2009 to 2020, Saudi Arabia



Note: Data on the rate of change of emissions from the top 14 countries in terms of global CE.

Figure 2.4. The rate of change in global CE (1980~2020 year).

Sources: Own elaboration and anaiysis.

was at a better level, and the value reached an average of 3.00 t/person. Russia ranked fourth, with an average of 12.47 t/person, accounting for 10.34% of the average total. Germany ranked fifth, with an average of 11.31 t/person, accounting for 9.38% of the average total; Japan ranked sixth, with an average of 9.14 t/person, accounting for 7.58% of the average total; the United Kingdom ranked seventh, with an average of 8.86t/person, accounting for 7.35% of the average capacity.

According to the above data, the CE of some developed countries are lower than those of developing countries because the utilization efficiency and optimal allocation of energy in some developed countries reduce the CE. Low-efficiency countries and some developing countries improve GDP through massive energy consumption and non-scientific resource allocation, intensifying the environmental impact while promoting economic growth (Lin et al., 2020).

The data analysis in Figure 2.4 shows that in terms of the rate of change in the seven countries, Saudi Arabia has a significant change range, ranging from -24.15% to 33.95%, of which eight abrupt change points are more than 12.00% in the negative range. Four sharp change points are more than 12.86% in the positive range. Indonesia ranks second, ranging from -24.15% to 18.12%, and the data analysis in Figure 2.3 shows that the top seven countries account for 77.83% of the global per capita total emission. nine steep change points are more than 13.66% in the positive range; Iran ranks third, ranging from -11.25% to 22.63%, and five sharp change points are more than 17.32% in the positive range; China ranks fourth, ranging from -5.02% to 16.65%. There are three strong change points in the positive field, which tend to be positive, and the negative range is small. Seven countries have favorable rates of change, and the top four are: China = 4.08% > India = 3.63% > Indonesia = 3.28% > Iran = 2.76%. Seven countries have negative rates of change, and the top three are: France = -1.87% > United Kingdom = -1.75% > Germany = -1.42%.

According to the data, half of the top 14 countries in CE have negative growth, with an average negative value of -1.09%, meaning that environmental governance has achieved specific results. Additionally, the other half is in positive change, with an average of 2.21%, indicating that environmental pollution is gradually increasing. The positive growth rate is 2.21 times the negative growth rate, indicating that "carbon neutrality" between countries cannot reduce global CE. Countries with high favorable growth rates will become significant countries with global environmental impact, which should strengthen environmental governance comprehensively.

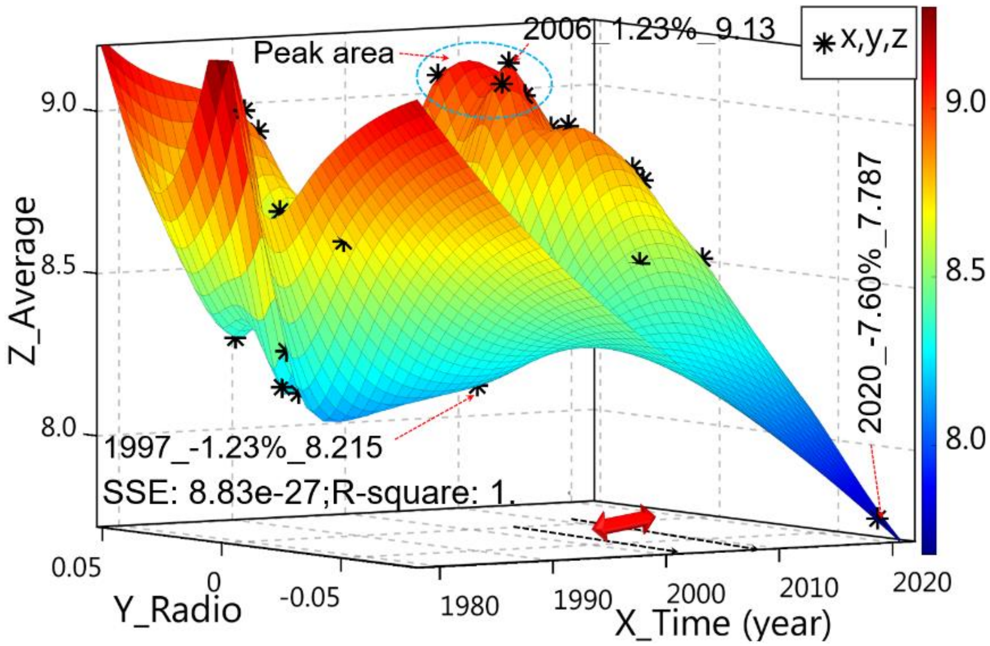


Figure 2.5. The analysis of thin-plate spline interpolant. (1980~2020 year).

Sources: Own elaboration and Matlab software anaiysis.

Figure 2.5 is the optimal fitting analysis of CE of 14 countries by using the method of Thin-plate spline interpolant, SSE = 8.83×10^{-27}, R-square = 1. The proper conclusion is accurate and reasonable about fitting. The research shows that the carbon emission peak was concentrated from 2004 to 2008, with an average value of 9.054,4 t, higher than the average value of 0.442,1 t in 14 countries; the lowest peak interval occurred from 1997 to 1998, lower than the average of 0.415,7 t in 14 countries.

The research data shows that the carbon emissions of 14 countries show different changes in different periods, and the overall dispersion does not appear. However, the average figures are higher than the benchmark average. Therefore, the overall trend is still showing growth trend. The top energy-consuming countries, such as the United States and China, need to increase the intensity of governance and improve control measures and policies.

2.1.2. Current status of carbon emissions in all continents

The sustainable impact assessment of global regionalization is of great significance. However, many uncertain factors related to spatial variability are to be solved, making it difficult to establish the research model framework system. Moreover, there is also the inconsistency between basic modeling assumptions and region, geography, time, and methodology, which ultimately affects the accuracy of research conclusions (Bulle et al., 2019).

This thesis analyses directly from the published data source (Our World in Data, 2021). It selects the database according to the distribution of six continents (Asia, Europe; Oceania; Africa; EU-27; South America, North America and South Africa) and the time interval (1970-2020 year).

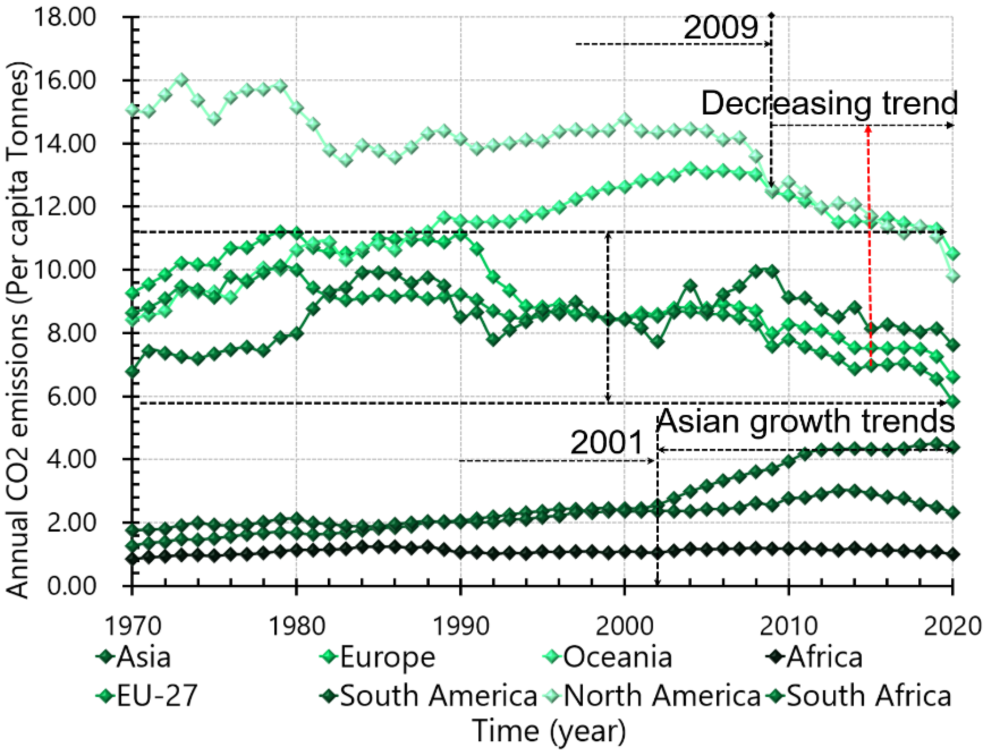


Figure 2.6. CE in all continents (1970~2020 year).

Sources: Own elaboration and anaiysis.

According to the data in Figure 2.6, the total CE per capita of each continent in 51 years ranked as follows: North America = 705.84 t > Oceania = 576.56 t > Europe = 474.28 t > South Africa = 434.71 t > EU-27 = 434.67 t > Asia = 133.32t > South America = 115.17 t > Africa = 55.74 t. The last three continents account for 10.38% of the total emissions.

North America accounts for 24.09% of the total emissions. It ranked first in the time interval (1970-2009). The overall linearity is in a slowly decreasing trend. From 2009 to 2020, there was a rapid decrease stage, reaching -2.14%. Oceania ranked second and was in an increasing location from 1970 to 2009, with an average growth rate of 1.02%; in 2010, there was a decreasing trend, with a decreasing rate of -1.52%, keeping pace with North America and ranking first in some time zones.

Europe, EU-27, and South Africa are in the third echelon, and their data are basically balanced with a slowly decreasing overall trend and an average decrease rate of -0.71%. Asia, Africa, and South America are in the fourth echelon with an average total emission of 101.41 t, 22.64% of the third echelon. However, all three continents are in the increasing stage, with an average growth rate of 1.16%. Asia showed a rapid growth trend from 2001 to 2020.

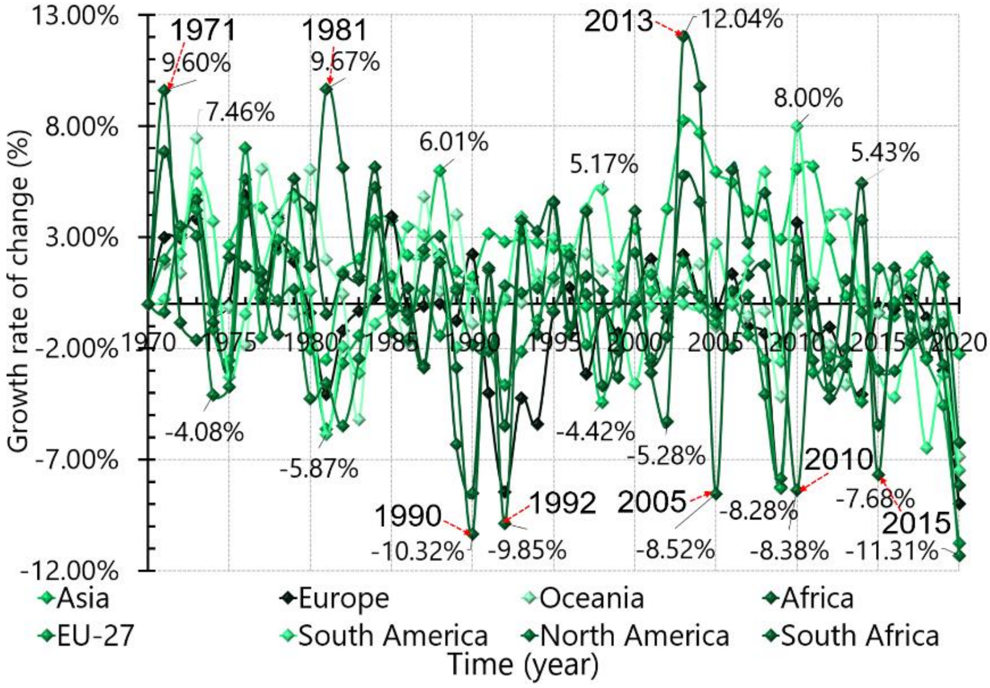


Figure 2.7. The rate of change in CE across continents (1970~2020 year).

Sources: Own elaboration and anaiysis.

Figure 2.7 shows the increasing changes in each continent. The change range of South Africa tends to be the first (10.32%-12.04%), with three positive peaks in 1971, 1981, and 2003 respectively, and five negative peaks in 1990, 1992, 2005, 2010, and 2015 respectively. It is in a positive growth stage, with a total growth rate of 0.35%. The increasing rate range of Africa is the smallest (-8.50% - 6.85%), with three positive peaks in 1971, 1976, 1984, and 2003 respectively, and three negative peaks in 1989, 1990, and 2020 respectively. It is in a positive growth stage, with the comprehensive growth rate of 0.38%. In a total growth rate, Europe (-0.62%), EU27 (-0.72%), and North America (-0.79%) showed negative growth.

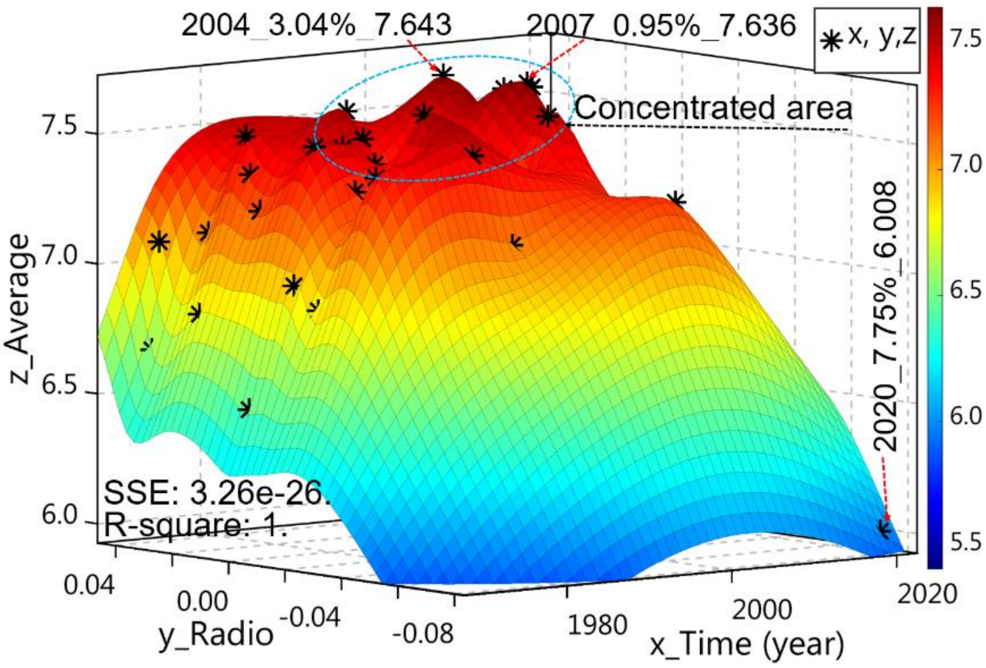


Figure 2.8. The analysis of thin-plate spline interpolant (1970~2020 year).

Sources: Own elaboration and Matlab software anaiysis.

Figure 2.8 is the fitting analysis within 51 years using the Thin-plate spline interpolant method, SSE = 3.258 × 10^{-26}, R-square = 1. The appropriate conclusion is accurate and reliable about fitting. The research shows that the peak interval of global CE is concentrated from 2003 to 2012, with the average per capita carbon emission of 7.427,3 t. The highest peak appeared in 2004 and 2007, and the lowest in 2020.

2.1.3. Carbon emissions in the construction industry

In 2019, the energy consumption of the global construction industry and related industries reached 35%, of which the CO_2 emission accounted for 38%. The total amount reached 10Gt, accounting for 28% of global CO_2 emissions (Mao et al., 2021). As the foundation of economic growth in all countries, the construction industry provides housing, traffic, social infrastructure, and cross-regional traffic connections (Prasad et al., 2019). The following three types of closely related inventory data are selected for research in the data source analysis: Manufacturing Construction Energy (MCE), Buildings, Transport.

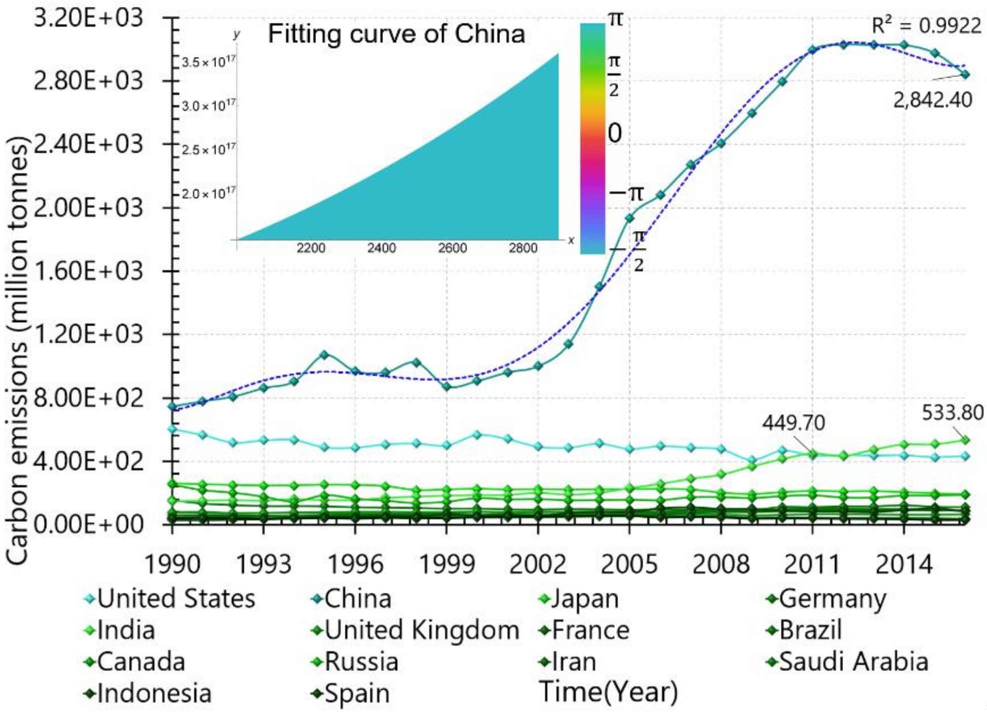


Figure 2.9. The analysis of manufacturing construction energy data (1990~2016 year).

Sources: Own elaboration and wolfram mathematica software anaiysis.

From Figure 2.9, it could be seen that China ranked first among the CE generated by MCE from 1990 to 2016, with a total amount of 46,482.4 million t and an annual average of 1,721.57 million t, accounting for 49.38% of the total emissions of 14 countries. It increased from 2003 to 2014 and gradually decreased after 2014. The United States ranked second, with 13,257.00 million t, accounting for 14.08% of the total emissions, and the annual average emission was 491.00 million t. The emission remains stable without significant change. India ranked third, with a total emission of 7,364.90 t, accounting for 7.82% of the total emission. The annual average emission was 272.77 million t. There has been a slowly increasing trend since 2003. The total emissions of the other 11 countries were 27.03 billion t, accounting for 28.71% of the total emissions.

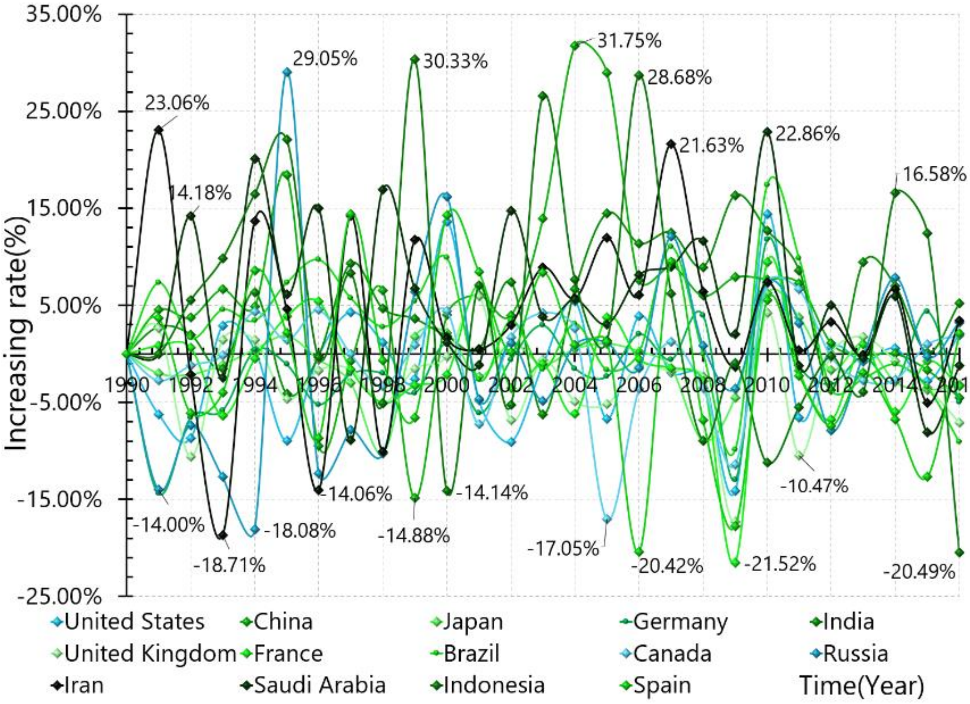


Figure 2.10. The rate analysis of manufacturing construction energy (1990~2016 year).

Sources: Own elaboration and anaiysis.

According to the data in Figure 2.10, the ranking of positive growth rate is 148.51% (China) > 148.24% (Saudi Arabia) > 135.715 (India) > 122.66% (Indonesia) > 102.52% (Iran) > 66.52% (Brazil), and the ranking of negative growth rate is -70.53% (United kingdom) > -51.86% (Germany) > -42.64% (France) > -29.00% (Japan) > -27.76% (United States) > -22.74% (Spain) > -16.41% (Russia) > -13.85% (Canada). The increasing rate of change in the positive range of 14 countries is 2.64 times that in the negative range, indicating that global CE are still at the peak of growth. Among the positive peak abrupt change values, Indonesia had five abrupt changes, with an average of 24.84%; Saudi Arabia had seven abrupt changes, with an average of 16.49%; Iran had nine abrupt changes, with an average of 13.25%. The negative abrupt change values were lower than three times.

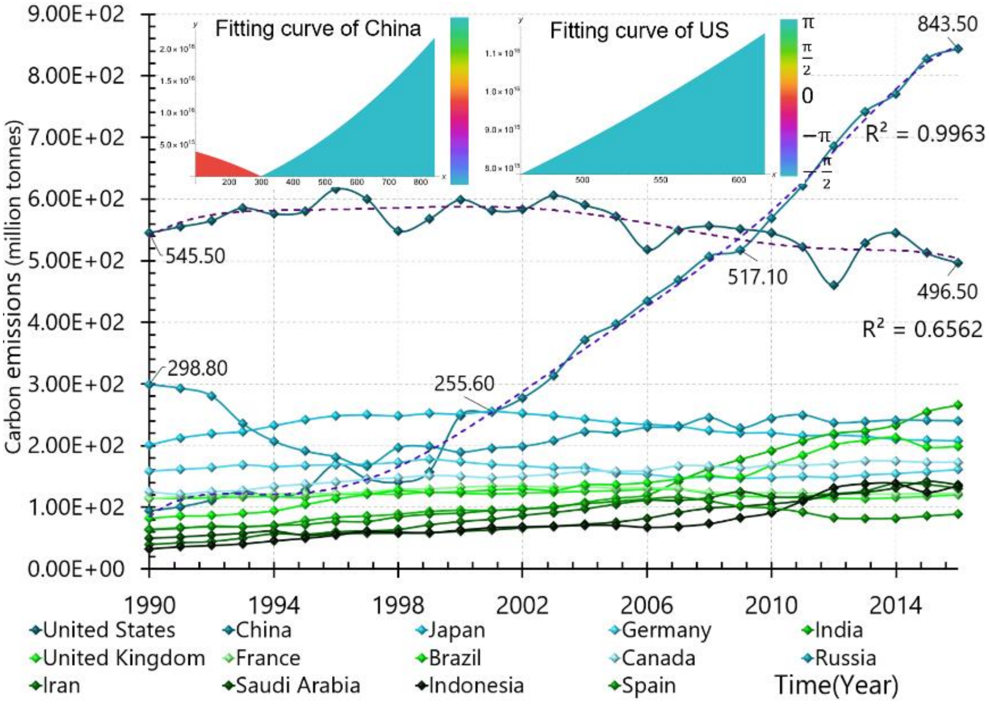


Figure 2.11. The analysis of buildings data (1990~2016 year).

Sources: Own elaboration and Wolfram mathematica software anaiysis.

According to the data in Figure 2.11, in terms of buildings, the total carbon emission of the United States is 15,055.60 million t, ranking first, with an annual average of 557.612 million t, accounting for 21.81% of the total of 14 countries. China ranks second, with a total emission of 10,138.80 million t, with an annual average of 375.51 million t, accounting for 14.69%. Japan ranks third, with a total emission of 6,222.30 million t, with a yearly average of 230.46 million t, accounting for 9.01% of the total; Russia ranks fourth, with a total emission of 6,108.40 million t, with an annual average of 226.24 million t, accounting for 8.85%

of the total. The above four countries account for 54.37% of the total emissions and will be critical countries in environmental governance. Indonesia has the lowest emission, with 2,040.90 million t and an annual average of 75.59 million tons, accounting for 2.96% of the total emissions.

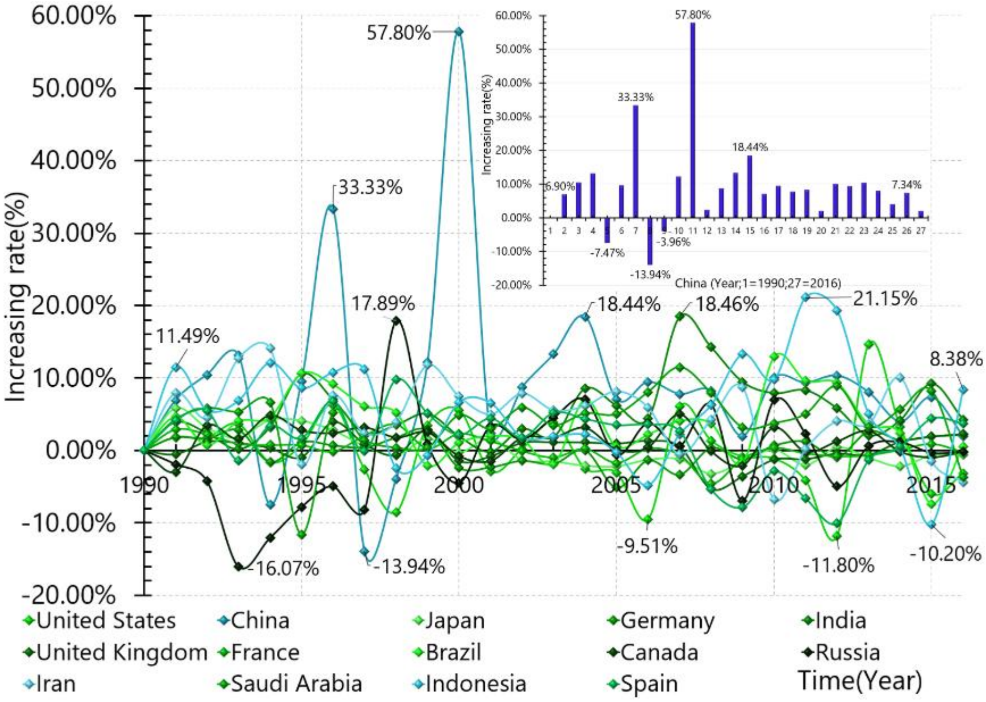


Figure 2.12. The rate analysis of buildings (1990~2016 year).

Sources: Own elaboration and anaiysis.

From Figure 2.12, the growth rate in 27 years is as follows: China ranked first, reaching 246.09%, with a yearly average of 9.11%; Indonesia ranked second, reaching 152.82%, with an annual average of 5.66%; India ranked third, reaching 147.65%, with an annual average of 5.47%. China had four abrupt positive changes, with the highest growth rate of 57.80% (2000), and CE increased by 91.10 million t. Indonesia had five abrupt positive changes, with the highest growth rate of 21.15% (2011), increasing by 19.20 million t. In terms of negative growth rate, Russia ranked first, with a total amount of -15.82% and a yearly average of -0.59%, followed by the United States, with an unlimited amount of -5.49% and an annual average of -0.20%. The ratio of positive and negative time zones is 45.07:1. The analysis shows that the carbon emission of the global building industry is still in the stage of growth with an enormous rate.

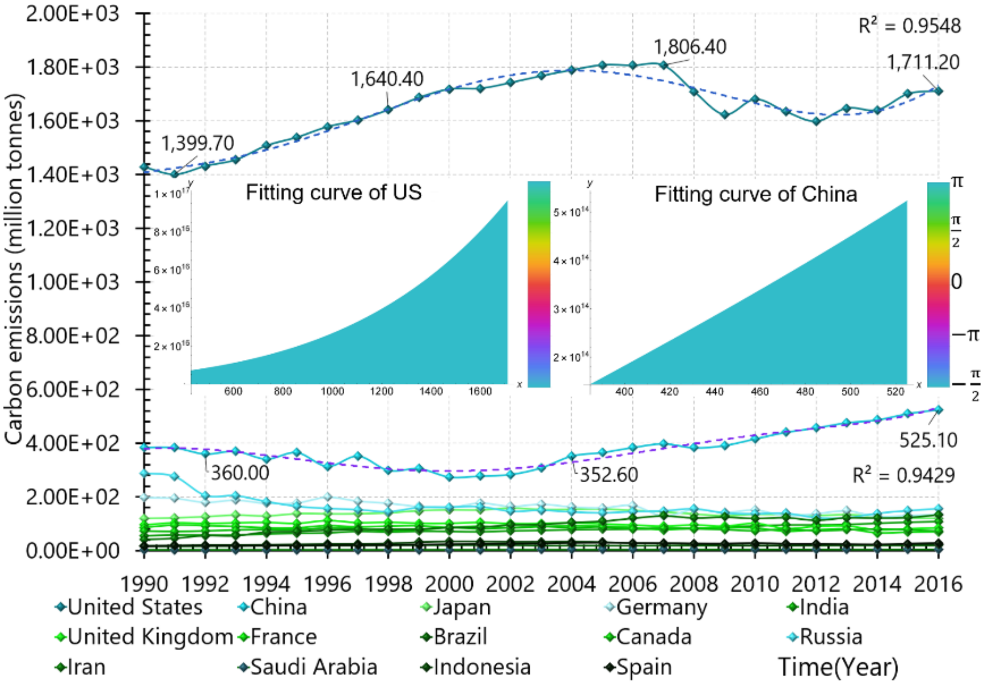


Figure 2.13. The analysis of transport data (1990~2016 year).

Sources: Own elaboration and Wolfram mathematica software analysis.

According to the CE in Figure 2.13, the United States ranks first, with a total emission of 44,356.80 million t, with an annual average of 1,642.84 million t, accounting for 54.89% of the total emissions. China ranks second, with a total emission of 10,208.60 million t, with an annual average of 378.10 million t, accounting for 12.63% of the total emissions; Germany and Russia rank third, with a total emission of 4,394.10 million t, with an annual average of 162.74 million t, accounting for 5.44% of the total emissions. The emissions from the above four countries accounted for 78.40% of the total. U.S. emissions and China's growth rates are slowly increasing, while the other 12 countries are in a solid phase.

Figure 2.14 shows that the change range of increasing rate is between 25.47% and 25.45%. Iran had the most effective increasing rate of 128.92% and three positive abrupt change peaks in 1992, 1994, and 2006. Saudi Arabia had the second-largest increase rate of 73.50% and two positive peaks in 1991 and 2011, respectively, with an average increasing rate of more than 17.95% and one negative rate of 10.00% (1992). Russia had the most prominent negative peak of -51.70%, two positive peaks in 1999 and 2014, respectively, and five negative peaks in 1992, 1994, 2002, 2009, and 2012 respectively, with an average of -13.78%, indicating that Russia is in the optimal area in this interval. Germany had the second-largest negative peak of -26.96%, three positive peaks in 1996, 2002, and 2008 respectively, and three negative peaks in 2007, 2011, and 2014 respectively, with an average of -16.91%, indicating that Germany has increased environmental governance and pollution control in this field after 2011.

Time	United States	China	Japan	Germany	India	United Kingdom	France	Brazil	Canada	Russia	Iran	Saudi Arabia	Indonesia	Spain
1990	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
1991	-1.91%	-0.36%	1.58%	-1.06%	5.14%	8.67%	11.21%	1.21%	-2.05%	-4.27%	10.81%	20.00%	3.59%	12.35%
1992	2.21%	-6.08%	3.43%	-7.84%	-1.18%	-2.60%	-2.52%	3.59%	2.51%	-25.47%	23.73%	-10.00%	5.94%	3.30%
1993	1.64%	2.89%	4.74%	4.61%	0.51%	2.27%	-3.23%	2.31%	4.76%	-0.58%	-1.43%	7.41%	0.93%	-4.26%
1994	3.62%	-7.86%	-2.49%	-6.43%	7.81%	1.74%	-6.01%	6.21%	1.56%	-10.61%	25.45%	3.45%	3.24%	5.56%
1995	2.05%	7.15%	6.42%	0.85%	2.99%	-3.80%	-0.24%	4.26%	-0.13%	-9.74%	3.19%	-3.33%	7.17%	-0.53%
1996	2.56%	-14.19%	-0.51%	12.16%	2.91%	10.95%	10.57%	1.02%	6.66%	-4.85%	7.58%	3.45%	6.28%	6.35%
1997	1.58%	12.36%	0.15%	-7.43%	8.32%	-7.38%	-5.91%	1.52%	-2.16%	-2.87%	3.00%	3.33%	1.57%	0.00%
1998	2.39%	-15.29%	2.41%	-4.39%	-3.43%	1.63%	4.00%	1.99%	-9.45%	-4.85%	1.27%	3.23%	3.49%	2.49%
1999	2.79%	2.21%	5.63%	-6.69%	4.26%	-3.68%	1.54%	4.88%	5.01%	10.82%	0.50%	0.00%	17.23%	5.83%
2000	1.87%	-10.22%	2.02%	-2.13%	-0.95%	-0.10%	-7.35%	-0.47%	9.16%	0.81%	7.47%	3.13%	7.67%	8.72%
2001	0.13%	1.35%	-0.33%	10.00%	-1.93%	3.24%	5.83%	0.93%	-4.14%	1.05%	1.27%	3.03%	-0.89%	4.22%
2002	1.26%	2.09%	4.44%	-6.83%	4.77%	-4.37%	-7.06%	-0.93%	4.44%	-10.62%	9.50%	2.94%	-3.59%	2.02%
2003	1.45%	8.78%	-3.24%	4.79%	2.68%	0.40%	5.81%	-10.28%	4.60%	2.73%	1.88%	2.86%	0.31%	2.78%
2004	1.24%	14.29%	0.26%	-5.67%	3.00%	3.07%	4.15%	2.60%	-4.18%	-4.32%	7.90%	2.78%	1.86%	8.11%
2005	1.06%	3.66%	0.92%	-2.15%	1.27%	-4.23%	-2.58%	-2.54%	2.59%	-2.22%	4.18%	8.11%	-4.56%	3.57%
2006	-0.09%	5.09%	-3.31%	5.45%	1.63%	-4.21%	-5.30%	0.00%	-7.69%	3.13%	10.58%	-2.50%	-10.19%	-5.17%
2007	0.02%	3.70%	-3.35%	-23.11%	0.37%	-4.50%	-10.04%	3.65%	3.98%	2.00%	7.34%	5.13%	0.00%	-2.55%
2008	-5.43%	-3.79%	-5.48%	18.62%	2.08%	5.15%	8.30%	0.00%	-2.63%	5.20%	-5.92%	4.88%	-10.28%	-2.99%
2009	-5.02%	2.19%	-4.41%	-7.10%	7.56%	-5.01%	2.16%	-1.51%	-3.81%	-10.15%	2.45%	2.33%	-14.62%	-1.54%
2010	3.53%	6.33%	3.84%	6.17%	3.57%	11.86%	-1.76%	1.02%	-5.36%	-2.07%	-3.99%	0.00%	-8.80%	6.64%
2011	-2.75%	5.84%	-1.11%	-13.74%	4.20%	-19.23%	-14.80%	1.52%	7.83%	1.61%	2.57%	15.91%	2.03%	-8.06%
2012	-2.21%	3.74%	-2.02%	5.67%	-0.10%	9.96%	7.84%	-0.50%	-7.13%	-12.07%	-8.10%	-9.80%	7.46%	-1.20%
2013	3.09%	4.24%	2.29%	7.54%	1.86%	1.44%	4.16%	2.00%	4.18%	0.00%	8.37%	-6.52%	5.56%	-3.63%
2014	-0.43%	2.18%	-4.25%	-13.88%	4.57%	-15.36%	-18.45%	0.49%	4.01%	13.48%	-0.81%	-2.33%	1.75%	-5.44%
2015	3.67%	4.83%	-4.91%	2.97%	3.89%	4.89%	3.98%	-1.46%	-3.48%	7.13%	1.64%	9.52%	4.31%	12.83%
2016	0.66%	2.86%	-1.48%	2.66%	2.15%	3.93%	2.50%	0.99%	-5.41%	5.04%	8.47%	6.52%	-4.55%	7.45%

Figure 2.14. The rate analysis of transport (1990~2016 year).

Sources: Own elaboration and anaiysis.

2.1.4. Summary of global carbon emissions data

The year 2020 is an essential milestone in global climate change policies. Countries have set emission reduction targets and new "net-zero carbon emission" and "carbon neutrality" targets by forcibly reducing or eliminating greenhouse gas emissions. The total amount of committed emission reduction accounts for 47% of the total global emissions (net-zero carbon emission: which means that the amount of greenhouse gas emissions generated is equal to the amount of greenhouse gas emissions eliminated from the atmosphere to achieve a net balance. Carbon neutrality: means achieving a balance between CE and carbon absorption in the atmosphere and providing equal carbon savings to balance the CE) (Janssens-Maenhout et al., 2017). The global greenhouse gas emissions of the construction industry are increasing exponentially; which has an increasing impact on the three pillars (society, economy, and environment) of SD and which has become the key to achieving the goal of SD (C. Brennan & J. Cotgrave, 2014).

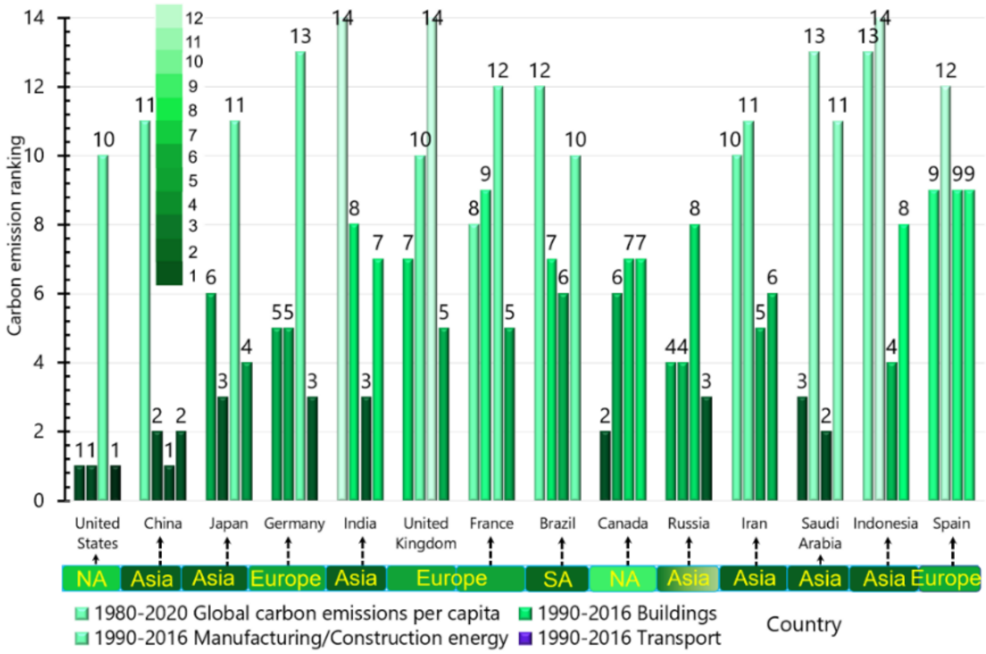


Figure 2.15. Global distribution of CE (1970~2021 year).

Sources: Own elaboration and anaiysis.

According to Figure 2.15, Asia accounts for 50% of the total emissions in the 14 countries, and seven countries are all in high emission areas. One country (Brazil) in South America is at Level 2; four countries in Europe are at Level 6; two countries in the North States are at Level 8; there is no country with high emission in the other four continents.

2.2. Global sustainable development research literature survey

The concept of "SD" has existed in indigenous culture for thousands of years, but it is a relatively new topic in academic works. UNESCO used this concept in 1970 to mark the interaction between humans and the environment (Waas et al., 2011). The idea appeared in *The World Conservation Strategy* in 1980, which stipulated the protection of biological resources to achieve SD. The term was highlighted in the Brundtland Report in 1987 and endorsed by UNGA (Agbedahin, 2019). It is now widely accepted as "the development that meets the needs of contemporary people without compromising the ability of future generations to meet their needs." Moreover, UN established the principle of the global development organization: "meet the basic needs of all people and provide opportunities for all people to realize a better life", which is often referred to as the three pillars ("environmental, economic and social issues") of SD (Ruan & Yan, 2022).

The traditional LCC is an investment calculus that first appeared in DoD in 1960. By the middle of 1980, LCC was applied to the development investment evaluation model of the construction industry under the environmental background (Abraham & Dickinson, 1998). *ISO15686* defines LCC as "a technology that can evaluate the comparative cost within a specific time range; consder all relevant economic factors, initial costs; and future service costs" (Henn, 1993). LCC object is the cost of the whole life cycle or the part of the life sequence for which a specific participant is responsible, a product, asset, or service system. It is mainly used in investment alternatives, optimal budget allocation, calculation trade-offs, uncertainty and risk identification, and hot topic selection. Its subject is the environmental and financial LCC, and its application depends on the goal (Kambanou & Sakao, 2020). Due to many uncertain factors and risks in the construction industry, the impact of current and future changes in ecological and social systems should be fully considered in decision-making, such as building materials, political decision-making, external market factors, procedures and regulations, and environmental protection, etc. In addition, LCC analysis should focus on: the understanding of concept and method, the availability and reliability of environmental data, and the perceptions and benefits of using LCC in investment decisions (Pernilla Gluch, 2004).

The Western Research Institute carried out the original LCA in 1969, called early ecological balance. Harry Teasley of Coca Cola proposed and applied the method and was also the first sponsor of "resource and environment profile analysis" (Hunt et al., 1992). In 1990, Europe developed a product-related environmental assessment similar to "from the cradle to the grave." The representative Nick de Oude is the founder of the European "Life Cycle Development Promotion Association." At the same time, the LCA technical framework, LCA conceptual framework of LCA impact analysis, life cycle data quality framework, and LCA guidelines were established (Klöpffer, 2006).

The overall framework system of LCA pays more attention to international standardization and globalization. The leadership is assumed and realized by *ISO*. Representatives of 24 countries have jointly formulated four international standards: *ISO14040-43* (Geerts et al., 2001). LCA is a method used to quantify the environmental impact of products, which considers production and consumption processes from the production of raw materials to the end of life. It can identify, evaluate, integrate, interpret and transmit the environmental impact data generated by relevant activities (Bicalho et al., 2017).

SIA originated from the *National Environmental Policy Act* in 1969. Mendoza proposed the evaluation index system in 1970. Since 1997, Delphi's Oracle has predicted and evaluated the impact of development (or planning and intervention) on society to maximize the benefits of growth and minimize development costs, especially those borne by the community (Vanclay, 2003a). It is specifically defined as "the process of analyzing, monitoring and managing the planned interventions (i.e., policies, programs, plans, projects) and the expected and unexpected social consequences of any social change, including the calling process of negative and positive interventions, to create a more sustainable and equitable biophysical and human environment." Essentially, it involves the harmful impact, development goal, and development process. It aims to maximize project benefits, minimize costs, and predict expected and unexpected positive and negative consequences by using accurate methods to formulate mitigation mechanisms for adverse impacts (Değirmenci & Evcimen, 2013).

SIA emphasizes the importance of impact and management on communities: including issues related to lifestyle, culture, and communities (such as cohesion, political system, environment, health and well-being, personal and property rights, and changes in fears and aspirations), which is a holistic and comprehensive impact assessment method (Vanclay, 2006).

Research methods play a vital role in the field of information science. The choice of specific techniques and quantity depends on the research objectives. Qualitative and quantitative research differ because the former is associated with relativism, hermeneutics, and constructivism. The latter is related to empiricism and positivism. A combination of the two is more suitable for interpretation and research for large amounts of data and community practice analysis (Fidel, 2008). For the accurate analysis and collection of data in survey research, Bernhard gave 13 analysis methods: historical research, case study, evaluation research, and others (Chu, 2015).

In the notes to the letter in Volume 510 of *Nature*, it is proposed that otlet founded bibliometrics, which is defined as "the measurement of all aspects related to the publication and reading of books and documents." The measurement refers to "elements that are easy to be measured observed in references such as objects, phenomena or facts, relations, and laws, etc." (Momesso & Noronha, 2017). Bibliometric analysis is used to automatically synthesize and analyze many scientific publications and identify core topics and first authors. Co-word analysis, institutional cooperation analysis, keyword, and structure analysis are used to infer the relationship to recognize the centrality and prominence of the literature (Shim et al., 2017). The theoretical model of bibliometrics is used to study the publications in this chapter.

The software CiteSpace 6.0 is used, an "information visualization" software developed by Dr. Chaomei Chen (Guo et al., 2022). It uses a Java application program to visualize and analyze citations and contents in scientific literature and then discovers, detects, and visualize the future emerging trends in this field. The application of the co-citation network clustering analysis method can track the development trend of research in a particular field. The mathematical model of the software application is spectral clustering and feature selection algorithms. The software is characterized by visualizing of conclusions, which can help more researchers understand trends, evolution, cognition, and social and collaborative activities. Many research literature uses CiteSpace as the primary tool of bibliometric analysis and has made perfect research conclusions and achievements (Madani & Weber, 2016).

Table 2.1 analyzes and compares the characteristics of three databases. Although WoS and Scopus have deficiencies in language and country, they can still better describe the scientific achievements in the fields covered in the interdisciplinary database, especially in engineering construction and natural science, it has high authority and recognition (Mongeon & Paul-Hus, 2016). Junwen Zhu (2020)analyzed the scientific literature published in WoS and Scopus from 2004 to 2018, finding little difference in the number of articles in the two databases, and they were widely used in meta-analysis-related research. In WoS, China and the United States account for 19.8% and 22.3%, respectively; in Scopus, the United States, the United Kingdom, and China account for 27.0%, 13.0%, and 2.07%, respectively. By category, medical fields, oncology, information, library science, and public, environment and health account for 14.8%, 7.5%, 6.1%, and 5.6%, respectively (in WoS); General and Internal accounts for 8.1%, and Pharmacology and Pharmacy, Surgery, Public, Environmental, and Occupational Health, as well as Information Science and Library Science account for 5.1%~7.1% (Scopus). Indicating that the relevant articles published by Scopus are more evenly distributed in published journals, so it is more suitable for robust research. This chapter uses the Scopus database to carry out retrieval literature analysis.

Table 2.1. Performance comparison of three kinds of literature databases

Name	WoS	Scopus	Ulrich
Date launched; Produce	1997,Clarivate Analytics	2004,Reed Elsevier	2021,Clarivate
Temporal coverage	1900 to present	1788 to present	1932 to present
No. of records	79 million (Core collection) 171 million (Platform)	82.4 million	336,000+
Country	United States	Netherlands	United States
Databases covered	Science Social science Arts Humanities	Life sciences Social sciences Physical sciences Health sciences	Multidisciplinary (all subjects)
Common language	9 kinds	6 kinds	15 kinds
Natural sciences and engineering	42.70%	32.90%	27.50%
Biomedical research	27.40%	30.60%	21.20%
Social sciences	21.30%	27.80%	36.00%
Arts and humanities	8.60%	8.70%	15.30%

Notes: 42.70% is proportion of literature published by the database in this research field (Kulkarni, 2009; Burnham, 2006; Singh Chawla, 2021; YU & SHAO, 2015; Wang et al., 2016).

Sources: Own elaboration, based on data from WoS, Scopus and Uirich.

2.2.1. Establish a research mathematical model

Establish a level range model to define the research indicators: strictly distinguish and judge the complex situation of SD in various continents; a multi-factor integral mathematical model is established to analyze and retrieve the literature data. The conclusion is used to compare the latest development situation.

Firstly, the classification and identification standard shall be established, and the level and judgment data (Table 2.2) shall be determined according to the model framework (*ISO14040*) of SD.

Table 2.2. Mathematical model identification parameters

1	2	Level 3	Level 4	Level 5
SD	LCC	Construction and installation engineering costs	Direct costs	7
			Equipment purchase fee	/
			Measure fee	1
			Enterprise management	2
			Fees	3
			Profit tax	/
			Special expenses	4
		Land use compensation		/
		Construction other	Project management fee	5
			Research and experiment	/
			Preliminary work	/
			Special evaluation	/
			Joint commissioning	/
			Production preparation	6
			Guaranteed management	/
			Insurance	/
		Preparation	Basic preparation	/
			Spread preparation	/
		Loan interest		/
	LCA	Survey and design	Personnel	Participate in all personnel
			Material	Office、Filed
			Machinery	Lease、Buy
			Project	Plan、Implementation plan
			Environment	Operation

		Processing and construction	Personnel	Participate in all personnel
			Material	Raw materials、Loss
			Machinery	Lease、Buy
			Project	Production Plan、Process
			Environment	Production、Transportation
		Construction and installation	Personnel	Participate in all personnel
			Material	Design、Assist
			Machinery	Lease、Buy
			Project	Construction design、Special plan
			Environment	Operation
		Operation and maintenance	Personnel	Participate in all personnel
			Material	Daily、Quarterly、Year
			Machinery	Lease、Buy
			Project	Maintain、Operation
			Environment	Operation
		Demolish	Personnel	Participate in all personnel
			Material	Scrapped、Loss
			Machinery	Lease、Buy
			Project	8
			Environment	Operation
	SIA	Fatalities	Country	Area、Community
		Young illiteracy	Country	Area、Community
		Bribery	Country	Area、Community
		Hygiene requirements	Country	Area、Community
		Immigration and personnel	Country	Area、Community

Notes: 1 = Winter and rainy seasons; Night special areas; Traffic interference; Construction assistance; Site transfer; 2 = Basic expenses; Main and non-staple foods;Travel expenses for family visits; Heating subsidies; Financial expenses; 3 = Pension; Unemployment; Medical treatment; Work injury; Housing; 4 = Construction site construction; Safe production; 5 = Owner management; Informa ionization; Supervision; Design document review; Test detection; 6 = Purchase of tools and equipment; Office and daily necessities; Personnel training; Emergency equipment guarantee; 7 = Labor costs; Material costs; Construction

machinery usage costs; 8 = Construction design; Emergency; Transportation; Environmental Protection (the above abbreviations only apply to Table 2.2).
Sources: Own elaboration and anaiysis.

Process of establishing multi factor integral mathematical model:

a) Consider the evaluation elements as factor sets, separate the hierarchy of keywords, and label them as factor set U (ZhiWu Zhou et al., 2020).

Eq.2.1 $$U=\{u_1, u_2, u_3\}$$

u_1 = LCC influencing factor; u_2 = LCA influencing factor; u_3 = SIA influencing factor.

b) Establish the evaluation set; determine each factor's level scores according to the division of five levels (the determination standard of scores is as follows: 1. A keyword appears in Level 1, 5 points will be added; $Level_2$: $Level_3$: $Level_4$: $Level_5$ = (+4) : (+3) : (+2) : (+1) point; 2. Points can be added accumulatively.) and establish the evaluation set as $V = \{v_1, v_2, v_3, v_4, v_5\}$.

c) Establish a single factor evaluation, and obtain the fuzzy subsets R_i, $R_i = r_{i1}, r_{i2}, r_{i3}, r_{i4}, r_{i5}$ (i =1,2,3,4,5) and 0≤r_{ij}≤1 (j = 1,2,3,4,5) by fuzzy evaluation for each factor. The single factor judgment matrix can be obtained as follows: V.

Eq.2.2 $$R_i=\begin{bmatrix} r_{11} & \cdots & \cdots & \cdots & r_{15} \\ r_{21} & \cdots & r_{23} & r_{24} & \vdots \\ \vdots & \vdots & \cdots & r_{34} & r_{35} \\ \vdots & r_{42} & \vdots & \cdots & \vdots \\ r_{51} & \cdots & r_{53} & \cdots & r_{55} \end{bmatrix}$$

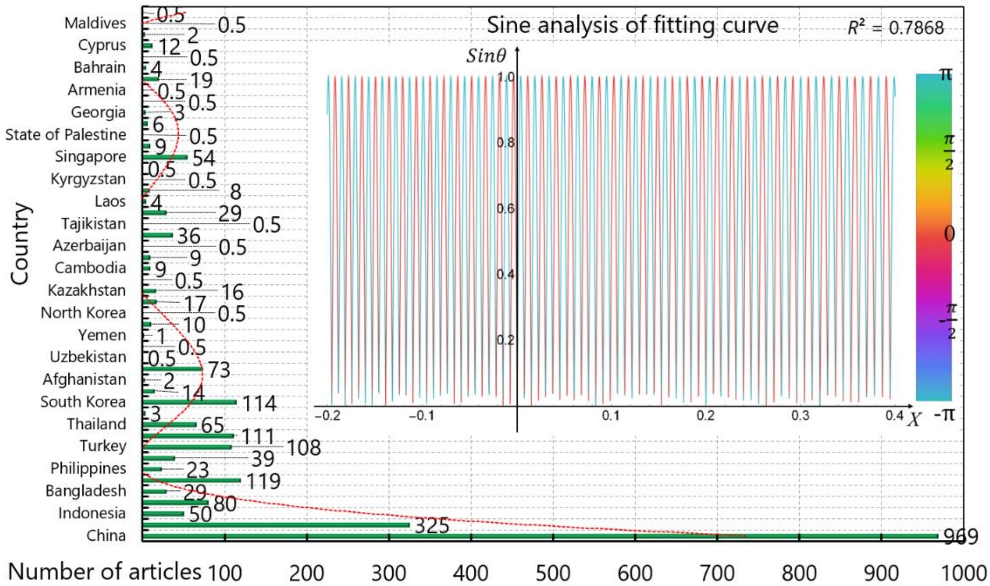
d) Carry out a comprehensive evaluation. For the different importance of multiple factors, different weights need to be given to each factor. According to practical experience, it constitutes a fuzzy subset A on U, which can be expressed as A = (a_1, a_2, a_3, a_4, a_5), where a_i (i = 1,⋯,5) is the countable of the i^{th} factor, and $\sum_{i=1}^{5} a_i$ = 1 is specified, so the mathematical model of fuzzy comprehensive judgment of influencing factors can be obtained as follows:

Eq.2.3 $$B = A \times R_i$$

B is the judgment data set of multi factor integral mathematical model.

2.2.2. State of European research

According to the analysis in 2.2, firstly, the core keywords and time interval of literature retrieval are determined; it is a crucial index analysis data, which is very important for the robustness and theoreticality of the research (Z. Zhang et al., 2021). The keywords selected include SD, Bridge; Article; 9,700 articles were retrieved. After 44 countries in Europe were selected to determine the research range, 4,224 articles were obtained, accounting for 43.55% of the total global publishing volume; and the time interval corresponds to 1993-2022.



Notes: European countries calculate according to the original United Nations standard to improve the robustness of research without considering other influencing factors.

Figure 2.16. Data distribution of publications in European countries (1993~2022 year).

Sources: Own elaboration, based on data from WoS, Scopus and Uirich.

According to Figure 2.16, the published literature is mainly concentrated in the United Kingdom, Germany, Italy, Spain, Netherlands, Sweden, and France.

The research results published in the above six countries accounted for 64.47% of the total number of publications in Europe. Among them, no published literature was retrieved in Moldova, Montenegro, Luxembourg, Andorra, Liechtenstein, and San Marino, reflecting the regional imbalance of publications. This phenomenon has triggered many series of social issues, For example, the time limit of journals and the effect of regional influence. Reviewers in the same region are more willing to accept articles in thearea and hold a positive attitude to receive and review (Gaston & Smart, 2018). Due to the trade surplus and deficit caused by the gap in science and technology, there is an unbalance in the global manufacturing industry and value chain, resulting in a series of social issues such as the gap between the rich and the poor, racial discrimination, etc. The imbalance of the economy has expanded unprecedentedly (Y. Li et al., 2020).

2.2.2.1. Mathematical model calculation of influencing factors

According to model in 2.2.1 and keyword scope, the scores are given, and the multi factor score matrix of R_i is determined as:

$$R_i = \begin{bmatrix} r_{SD1} & r_{SD2} & r_{SD3} & r_{SD4} & r_{SD5} \\ r_{LCC1} & r_{LCC2} & r_{LCC3} & r_{LCC4} & r_{LCC5} \\ r_{LCA1} & r_{LCA2} & r_{LCA3} & r_{LCA4} & r_{LCA5} \\ r_{SIA1} & r_{SIA2} & r_{SIA3} & r_{SIA4} & r_{SIA5} \end{bmatrix} = \begin{bmatrix} 20 & 12 & 6 & 4 & 7 \\ 5 & 8 & 5 & 2 & 1 \\ 5 & 14 & 9 & 18 & 8 \\ 35 & 12 & 9 & 16 & 6 \end{bmatrix}.$$

The evaluation matrix obtained is: $R = \begin{bmatrix} 0.41 & 0.24 & 0.12 & 0.08 & 0.14 \\ 0.24 & 0.38 & 0.24 & 0.10 & 0.05 \\ 0.09 & 0.26 & 0.17 & 0.33 & 0.15 \\ 0.45 & 0.15 & 0.12 & 0.21 & 0.08 \end{bmatrix}$

According to the important difference of indicators at all levels in SD, to determine the weight of influencing factors, zhou.et al. (2022b) used the evaluation framework and theoretical model to conclude that the final LCIA, LCCA, and SILA were affected by many factors and determined A = {0.4 0.3 0.2 0.1}.

The final comprehensive evaluation set is $B = RA = [0.4 \quad 0.3 \quad 0.2 \quad 0.1] \times \begin{bmatrix} 0.41 & 0.24 & 0.12 & 0.08 & 0.14 \\ 0.24 & 0.38 & 0.24 & 0.10 & 0.05 \\ 0.09 & 0.26 & 0.17 & 0.33 & 0.15 \\ 0.45 & 0.15 & 0.12 & 0.21 & 0.08 \end{bmatrix} = [0.299 \quad 0.277 \quad 0.166 \quad 0.149 \quad 0.109]$

2.2.3. State of Americas research

The keywords for analysis of Americas include: SD, Bridge; Article. A total of 9,700 articles were retrieved. After 35 countries in Europe were selected to determine the research range, 2,155 articles were obtained, and the corresponding time zone ranges from 1986 to 2022.

From Figure 2.17, it can be seen that in the literature published in the Americas, the United States, Canada and Brazil accounted for 64.18%, 17.82%, and 7.05%, respectively, with a total of 89.05%. Among 35 countries, ten countries did not publish articles; 15 countries published less than ten articles. Education and scientific research expenditure, medical expenditure, and population growth, has broken through the balance standard and is developing rapidly to extremes. This phenomenon in the Americas is more severe than in Europe (Zaman & Shamsuddin, 2018).

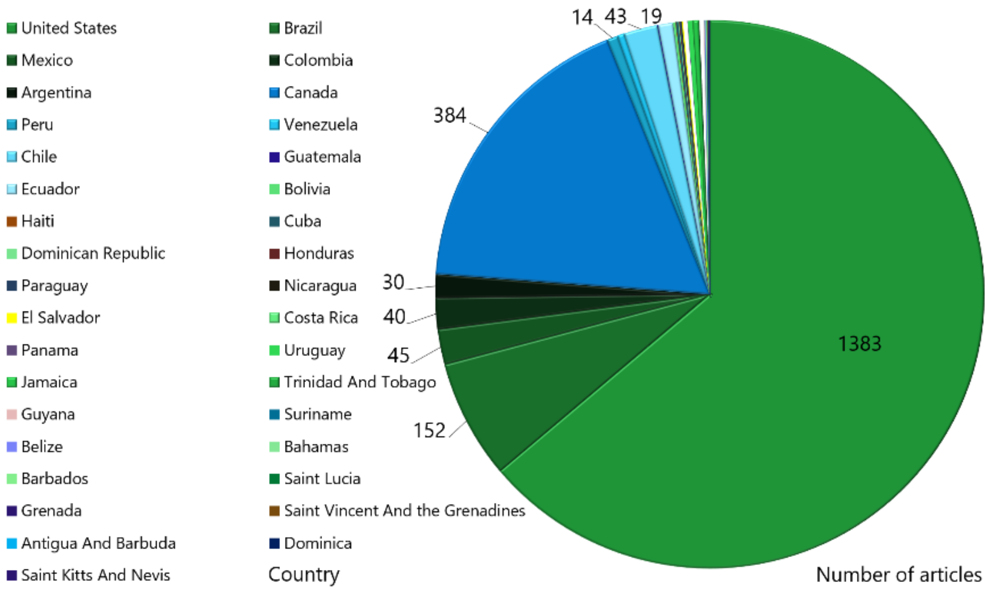


Figure 2.17. Data distribution of publications in Americas countries (1986~ 2022 year).
Sources: Own elaboration, based on data from WoS, Scopus and Uirich.

From Figure 2.17, it can be seen that in the literature published in the compr-

2.2.3.1. Mathematical model calculation of influencing factors

According to model in 2.2.1 and keyword scope, the scores are given, and the multi factor score matrix of R_i is determined as: $R_i = \begin{bmatrix} r_{SD1} & r_{SD2} & r_{SD3} & r_{SD4} & r_{SD5} \\ r_{LCC1} & r_{LCC2} & r_{LCC3} & r_{LCC4} & r_{LCC5} \\ r_{LCA1} & r_{LCA2} & r_{LCA3} & r_{LCA4} & r_{LCA5} \\ r_{SIA1} & r_{SIA2} & r_{SIA3} & r_{SIA4} & r_{SIA5} \end{bmatrix} = \begin{bmatrix} 25 & 28 & 12 & 18 & 1 \\ 5 & 12 & 3 & 4 & 2 \\ 5 & 8 & 3 & 14 & 7 \\ 5 & 18 & 27 & 34 & 7 \end{bmatrix}.$

The evaluation matrix obtained is: $R = \begin{bmatrix} 0.30 & 033 & 0.14 & 0.21 & 0.01 \\ 0.19 & 0.46 & 0.12 & 0.15 & 0.08 \\ 0.14 & 0.22 & 0.08 & 0.38 & 0.19 \\ 0.05 & 0.20 & 0.30 & 0.37 & 0.08 \end{bmatrix}.$

Determining $A = \{0.4 \;\; 0.3 \;\; 0.2 \;\; 0.1\}$.

The final comprehensive evaluation set is $B = RA = [0.4 \quad 0.3 \quad 0.2 \quad 0.1] \times \begin{bmatrix} 0.30 & 0.33 & 0.14 & 0.21 & 0.01 \\ 0.19 & 0.46 & 0.12 & 0.15 & 0.08 \\ 0.14 & 0.22 & 0.08 & 0.38 & 0.19 \\ 0.05 & 0.20 & 0.30 & 0.37 & 0.08 \end{bmatrix} = [0.21 \quad 0.334 \quad 0.138 \quad 0.242 \quad 0.074]$

-ehensive evaluation: Americas obtained the research results of SD in 1986, and the research peak was from 2004 to 2012. The follow-up still showed an increasing trend. However, the research scope is narrower than in Europe, and the diversity needs to be strengthened. There are rich research results in the field of environment, which is worthy of learning by global scientific researchers, still, the regionality of the research presents profound polarization, accounting for 22.22% of the world.

2.2.4. State of Asia research

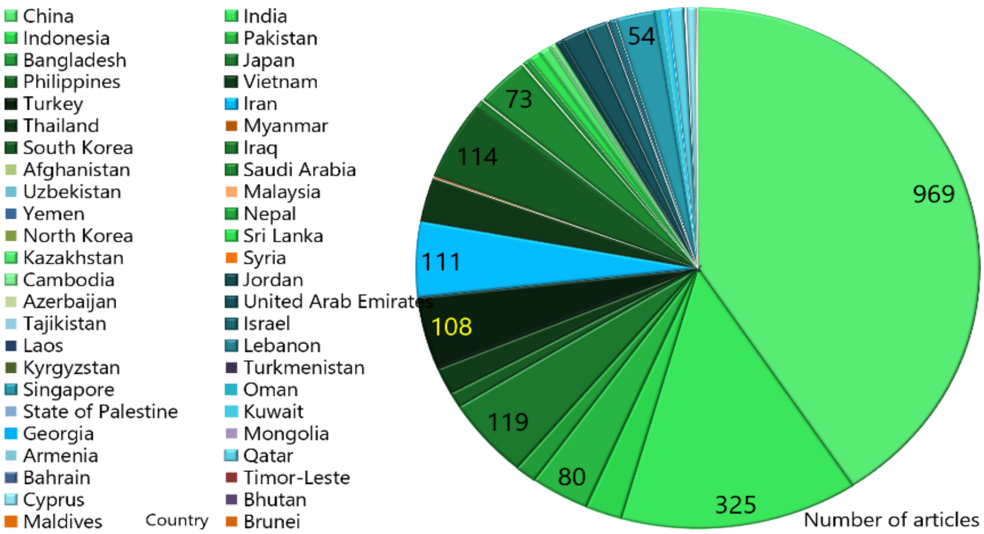


Figure 2.18. Data distribution of publications in Asia countries and regions (1996 ~ 2022 year).

Sources: Own elaboration, based on data from WoS, Scopus and Uirich.

The keywords selected for Asia include: SD, Bridge; Article. 7,900 articles were retrieved. After 48 countries in Asia were selected to determine the research range, 2,380 articles were obtained (Figure 2.18), and the corresponding time zone ranges from 1996 to 2022. According to the literature, 14 countries did not publish research results, and the number of publications of 6 countries accounted for 73.39% of the total.

China and India account for 40.73% and 13.66% respectively, which are the most significant contributors to the research literature.

2.2.4.1. Mathematical model calculation of influencing factors

According to model in 2.2.1 and keyword scope, the scores are given, and the multi factor score matrix of R_i is determined as:

$$R_i = \begin{bmatrix} r_1 & \cdots & r_n \\ \vdots & \vdots & \vdots \\ r_i & \cdots & r_{ni} \end{bmatrix}$$

$$R_i = \begin{bmatrix} r_{SD1} & r_{SD2} & r_{SD3} & r_{SD4} & r_{SD5} \\ r_{LCC1} & r_{LCC2} & r_{LCC3} & r_{LCC4} & r_{LCC5} \\ r_{LCA1} & r_{LCA2} & r_{LCA3} & r_{LCA4} & r_{LCA5} \\ r_{SIA1} & r_{SIA2} & r_{SIA3} & r_{SIA4} & r_{SIA5} \end{bmatrix} = \begin{bmatrix} 15 & 8 & 9 & 2 & 1 \\ 5 & 4 & 6 & 2 & 1 \\ 5 & 4 & 9 & 26 & 5 \\ 5 & 16 & 18 & 16 & 2 \end{bmatrix}.$$

The evaluation matrix obtained is: $R = \begin{bmatrix} 0.43 & 0.23 & 0.26 & 0.06 & 0.03 \\ 0.28 & 0.22 & 0.33 & 0.11 & 0.06 \\ 0.10 & 0.08 & 0.18 & 0.53 & 0.10 \\ 0.09 & 0.28 & 0.32 & 0.28 & 0.04 \end{bmatrix}.$

Determining A = {0.4 0.3 0.2 0.1}.

The final comprehensive evaluation set is $B = RA = [0.4 \quad 0.3 \quad 0.2 \quad 0.1] \times$

$$\begin{bmatrix} 0.43 & 0.23 & 0.26 & 0.06 & 0.03 \\ 0.28 & 0.22 & 0.33 & 0.11 & 0.06 \\ 0.10 & 0.08 & 0.18 & 0.53 & 0.10 \\ 0.09 & 0.28 & 0.32 & 0.28 & 0.04 \end{bmatrix} = [0.285 \quad 0.202 \quad 0.271 \quad 0.191 \quad 0.054]$$

Comprehensive evaluation: Asia started the research on SD relatively late, and has published relevant research literature since 1996. The research peak is from 2008 to 2017, and then tends to the stage of medium growth. The research scope involves many fields and shows diversity. There is a lack of detailed and in-depth research on SD and high-quality breakthrough research results.

2.2.5. State of Oceania research

The keywords selected for Oceania include: SD, Bridge; Article. 9,700 articles were retrieved, and 615 articles were published, accounting for 6.34% of the total global publications.

There are 15 countries in the continent, of which seven countries have published articles, and the rest did not publish any articles. Among them, Australia, New Zealand, and Western New Guinea (Indonesia) account for 80.06%, 9.11%, and 7.85%, respectively, with 97.02% (Figure 2.19).

The first research time is 1988, earlier than Europe and Asia. The total number of published literature is low. The core time zone of Oceania's sustainable development literature is concentrated in 2005-2016, and the research focuses on sustainable economy, management, ecological control, and the construction industry. Comprehensively presents the diversity of research results. Label (LLR)=82.82; the data is low, but the scope and research director of the research field is prominent, with a high level of paradigm. Demonstrates that the implementation of strategies to achieve the SDGs is based on ecosystem services and the co-benefits that may be provided and that these benefits and policies often drive the implementation of SDG strategies.

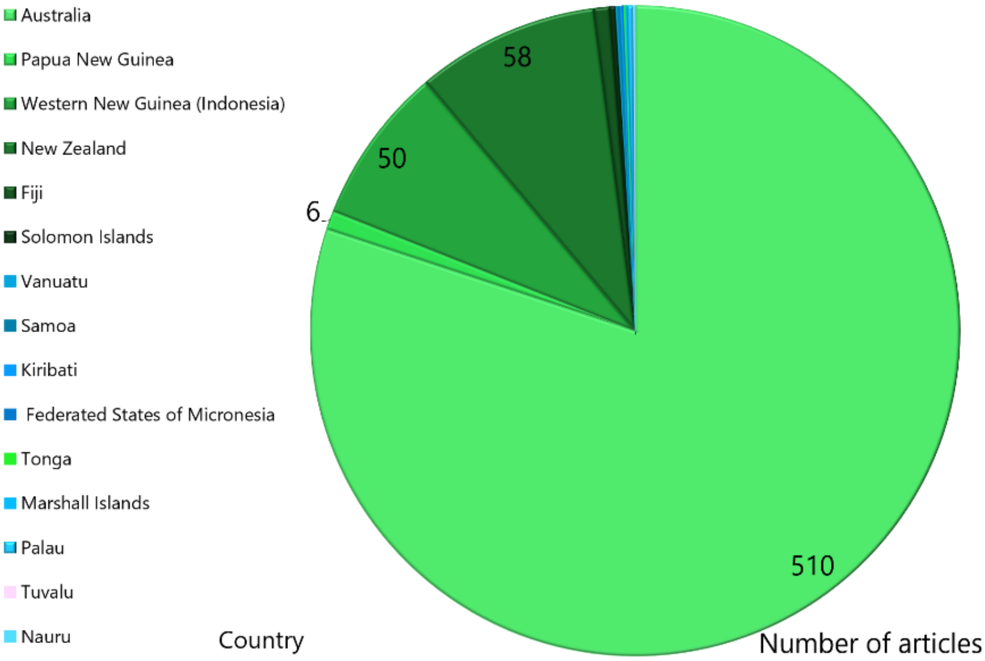


Figure 2.19. Data distribution of publications in Oceania countries (1988~2022 year).

Sources: Own elaboration, based on data from WoS, Scopus and Uirich.

2.2.5.1. Mathematical model calculation of influencing factors

According to the model in 2.2.1 and keyword scope, the scores are given, and the multi-factor score matrix of R_i is determined as:

$$R_i = \begin{bmatrix} r_{SD1} & r_{SD2} & r_{SD3} & r_{SD4} & r_{SD5} \\ r_{LCC1} & r_{LCC2} & r_{LCC3} & r_{LCC4} & r_{LCC5} \\ r_{LCA1} & r_{LCA2} & r_{LCA3} & r_{LCA4} & r_{LCA5} \\ r_{SIA1} & r_{SIA2} & r_{SIA3} & r_{SIA4} & r_{SIA5} \end{bmatrix} = \begin{bmatrix} 35 & 16 & 6 & 6 & 1 \\ 5 & 8 & 3 & 2 & 1 \\ 10 & 8 & 6 & 20 & 9 \\ 15 & 40 & 18 & 14 & 2 \end{bmatrix}.$$

The evaluation matrix obtained is: $R = \begin{bmatrix} 0.55 & 0.25 & 0.09 & 0.09 & 0.02 \\ 0.26 & 0.42 & 0.16 & 0.11 & 0.05 \\ 0.19 & 0.15 & 0.11 & 0.38 & 0.17 \\ 0.17 & 0.45 & 0.20 & 0.16 & 0.02 \end{bmatrix}.$

Determining $A = \{0.4 \ \ 0.3 \ \ 0.2 \ \ 0.1\}$. The final comprehensive evaluation set is

$$B = RA = [0.4 \quad 0.3 \quad 0.2 \quad 0.1] \times \begin{bmatrix} 0.55 & 0.25 & 0.09 & 0.09 & 0.02 \\ 0.26 & 0.42 & 0.16 & 0.11 & 0.05 \\ 0.19 & 0.15 & 0.11 & 0.38 & 0.17 \\ 0.17 & 0.45 & 0.20 & 0.16 & 0.02 \end{bmatrix} = [0.354 \quad 0.301 \quad 0.126 \quad 0.161 \quad 0.059]$$

Comprehensive evaluation: There are few publications on SD in Oceania, and the first publication time is 1988, earlier than that in Europe and Asia. The scope of research is broader than that in Europe and America. In particular, the cross-regional cooperative research is ahead of other continents, and the cooperation density is 0.010,7, which appears for the first time in the literature analysis. The cooperation density in different regions is less than 0.009, and there is an imbalance in scientific research, which is higher than that in other continents. Since 2016, the research in this field has developed slowly, and the research on green, carbon neutralization, and ecological optimization is missing.

2.2.6. State of Africa and Antarctica research

The keywords selected for Africa and Antarctica include: SD, Bridge; Articles. 9,700 articles were retrieved, and 327 papers were published, accounting for 3.37% of the total global publications. According to the 1959 "Antarctic Treaty," Antarctica will always support peace and will not become a place or object of international disputes, which is in the interests of all humankind.

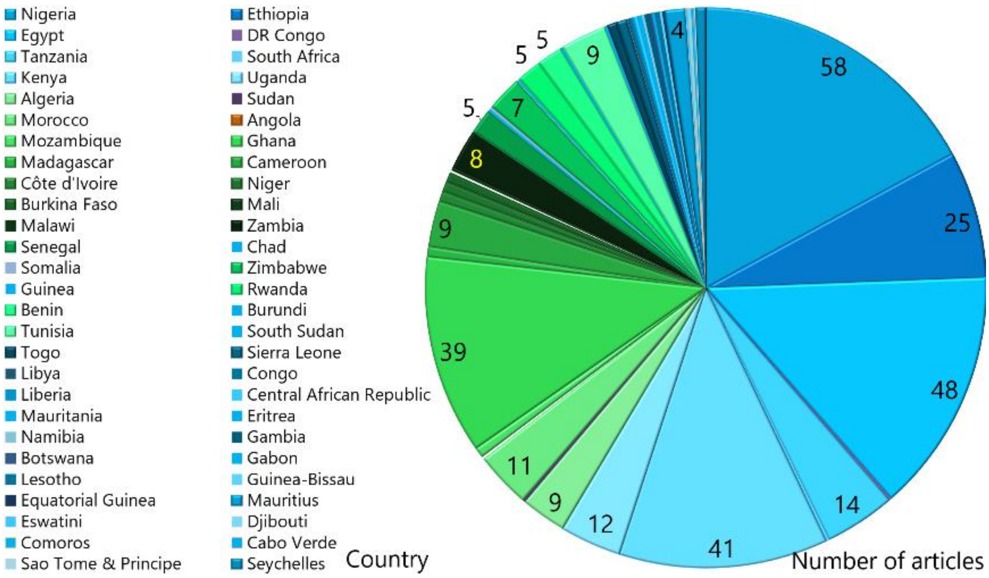


Figure 2.20. Data distribution of publications in Africa and Antarctica countries (1996~2022 year).

Sources: Own elaboration, based on data from WoS, Scopus and Uirich.

It stipulates that we should deny the claim of territorial sovereignty over Antarctica or establish the basis of any sovereign rights (Dodds, 2019). Due to this Treaty, Antarctica did not publish any literature. There are 54 countries in Africa, of which 27 did not publish any literature. Nigeria and Egypt account for 17.06% and 14.12%, respectively, and Nigeria, Egypt, Kenya, Ghana, and Ethiopia account for 62.06% of the total in Africa (see Figure 2.20 for detailed data).

The data shows that Africa has a low number of published research results in this field and a low impact factor of published literature. A comprehensive assessment of the scientific and technological strength and the number of researchers in less developed countries is the soft power that affects the region's economic development.

2.2.6.1. Mathematical model calculation of influencing factors

According to model in 2.2.1 and keyword scope, the scores are given, and the multi factor score matrix of R_i is determined as: $R_i = \begin{bmatrix} r_{SD1} & r_{SD2} & r_{SD3} & r_{SD4} & r_{SD5} \\ r_{LCC1} & r_{LCC2} & r_{LCC3} & r_{LCC4} & r_{LCC5} \\ r_{LCA1} & r_{LCA2} & r_{LCA3} & r_{LCA4} & r_{LCA5} \\ r_{SIA1} & r_{SIA2} & r_{SIA3} & r_{SIA4} & r_{SIA5} \end{bmatrix} = \begin{bmatrix} 35 & 16 & 9 & 4 & 3 \\ 5 & 4 & 3 & 2 & 1 \\ 10 & 12 & 9 & 12 & 4 \\ 20 & 28 & 21 & 12 & 3 \end{bmatrix}$.

The evaluation matrix obtained is: $R = \begin{bmatrix} 0.52 & 0.24 & 0.13 & 0.06 & 0.04 \\ 0.33 & 0.27 & 0.20 & 0.13 & 0.07 \\ 0.21 & 0.26 & 0.19 & 0.26 & 0.09 \\ 0.24 & 0.33 & 0.25 & 0.14 & 0.04 \end{bmatrix}$.

Determining A = {0.4 0.3 0.2 0.1}.

The final comprehensive evaluation set is $B = RA = [0.4 \quad 0.3 \quad 0.2 \quad 0.1] \times \begin{bmatrix} 0.52 & 0.24 & 0.13 & 0.06 & 0.04 \\ 0.33 & 0.27 & 0.20 & 0.13 & 0.07 \\ 0.21 & 0.26 & 0.19 & 0.26 & 0.09 \\ 0.24 & 0.33 & 0.25 & 0.14 & 0.04 \end{bmatrix} = [0.373 \quad 0.262 \quad 0.175 \quad 0.129 \quad 0.059]$

Comprehensive evaluation: Africa and Antarctica are the regions with the least published literature in the world. The earliest literature was published in 1996, the same time as Asia. It is the latest of the six continents. The literature is concentrated from 2006 to 2018, and the scope of research is the narrowest. The core research is disconnected from the development of science and technology. The research on published literature shows a slowly increasing trend, and there is a significant gap between Europe and the Americas. The core issues restricting

SD in Africa are as follows: recognizing and adapting to the challenges of rapid urbanization; ensuring that environmental protection is as crucial as economic development in Africa; developing the capacity of African planning agencies to identify threats and sustainably manage rapid and unguided urbanization in a sustainable manner, and empowering planning agencies to continue to implement urban policies in the face of complexity and uncertainty; improving the role and participation of urban residents in the formulation and implementation of sustainable urban development policies (Cobbinah et al., 2015).

2.2.7. Comparative analysis of six continents' mathematical models

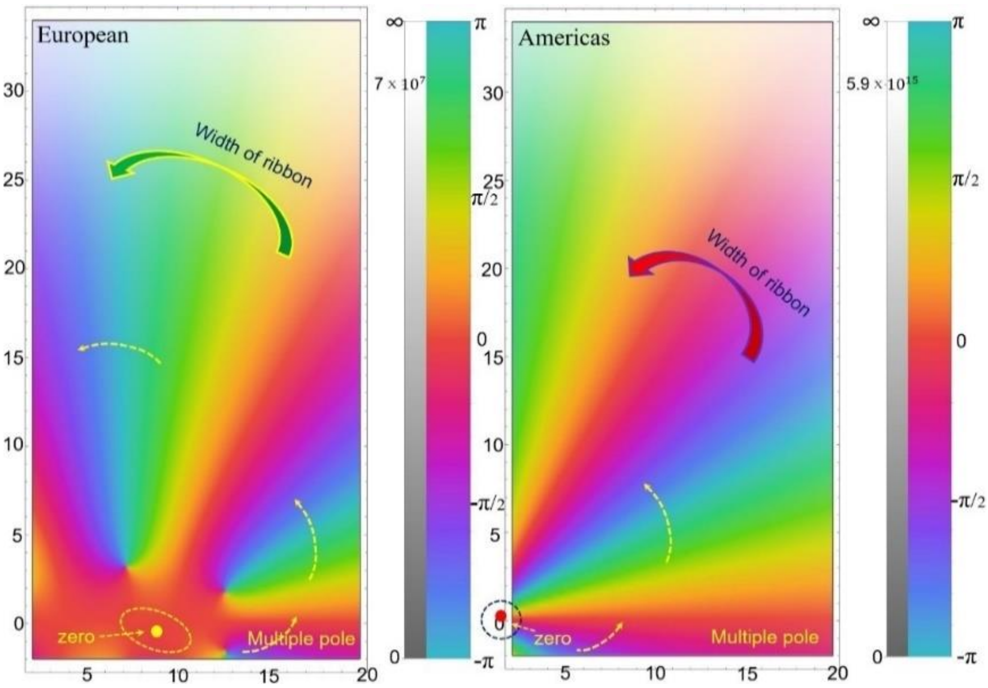
In 2.2.6, the robustness of published literature in six continents is analyzed. To more clearly explore the relationship between LLR and publishing time interval, the ComplexPlot mathematical model is introduced to identify the characteristics of published literature in each continent.The core data of the research model are characterized by cyclic color function and interval range to improve the robustness of the study (Abdulhay et al., 2020).

The analysis shows that (Figure 2.21):

a) There is no Zero-point in the function cycle of six continents, and the imaging points of Zero-point within the time zone are European and Asia; the Zero point of the other four continents is outside the time zone. According to the principle of the mapping function, the ranking of points is Africa and Antarctica < Americas < Oceania. The above research conclusions show that there are discreteness and imbalance in the published results of SD research in the six continents, of which Oceania is the largest region, and European has the most representative research results.

b) The color bands determine the quantity and quality of publications. The number of color bands in each continent is: European = 2.25; Americas = 1.3; Asia = 1.38; Oceania = 2.0; Africa and Antarctica = 1.45. The base points of Europe and Asia are within the time zone, and those of the Americas and the other three continents are outside the time zone, which is divided into two groups. The number of publications in Europe is higher (19.02%) than in Asia. There is a important opening in the dispersion of information between America and Asia, still, it is evident that the color band uniformity of America is better than that of Asia, and there is also little difference in the number of publications. Other continents ranked last.

c) The paradigms and other characteristics of published literature can be determined by the robustness of color bandwidth and distribution. The color bandwidth of Europe is more comprehensive, the color of the color band has a uniform transition, and the color frequency is high, judging that Europe has the best robustness and continuity of the published literature and the entire field. In terms of the Americas and Asia, the first is that the color cycle is similar, still, the color band uniformity of the Americas is better than that of Asia, indicating that the quality of publications is higher than that of Asia; that is, the high-quality literature is more than that of Asia. The total number of publications is the same as that in Asia, But the time interval of publications is quite different, and the time of the Americas is earlier than Asia. The robustness of the Americas is generally higher than that of Asia because of the narrow color bandwidth and poor color uniformity of Asia. Oceania and Africa have the most limited color bandwidth, which is significantly thinner than the first three continents, indicating that the quality and quantity of published articles are low, and the scope of research is limited. However, it can be clearly seen that the transition of the color band is smoother than that of the first three continents, indicating that the cooperation of research literature and scientific research institutions is better



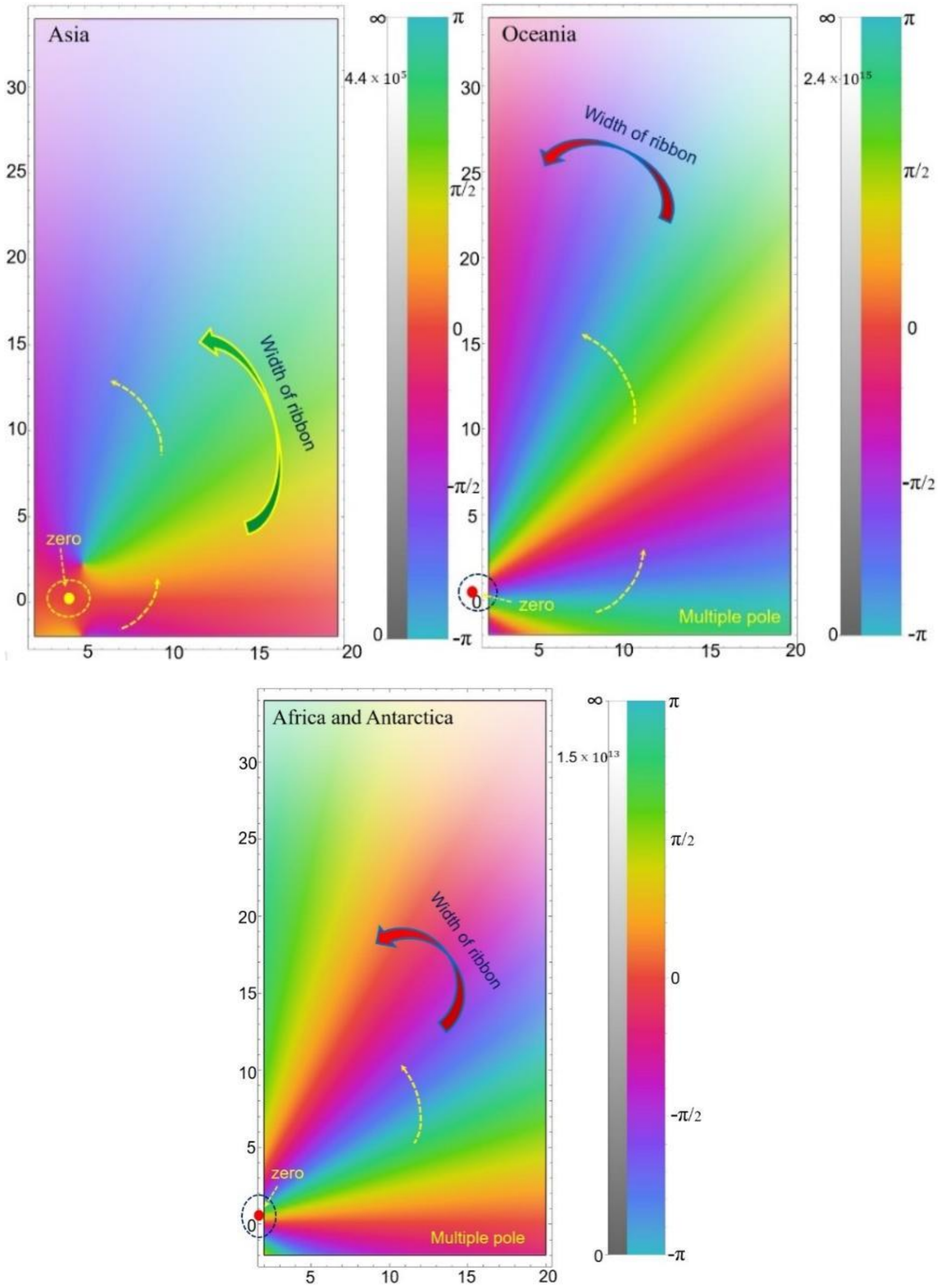


Figure 2.21. Six continents mathematical models.

Sources: Own elaboration and Wolfram mathematica software analysis.

than that of other continents.

2.3. Summary of this chapter

Based on the analysis of global carbon emission data, this chapter studies the per capita CE and environmental governance of the top 14 countries in the world; The research on regional data shows that: North America accounts for 24.09% of the total global emissions, ranking first in the time interval (1970-2009), and is in a slowly decreasing stage as a whole; from 2009 to 2020, there was a rapid decrease stage, reaching -2.14%. Oceania was in an increasing location from 1970 to 2009, with an average growth rate of 1.02%; since 2010, it has been in the decreasing stage, with a decrease rate of -1.52%, ranking second.

China ranked first among the CE generated by MCE from 1990 to 2016, with 46,482.4 million t and an annual average of 1,721.57 million t, accounting for 49.38% of the total emissions of 14 countries. It increased from 2003 to 2014 and decreased after 2014. The United States ranked second, with 13,257.00 million t, accounting for 14.08% of the total emissions, and the annual average emission was 491.00 million t.

This thesis analyzes the current situation of published literature on global SD and the future research direction and field. European published literature has the best robustness and continuity and the entire area. The quality of Asian publications is superior to that of American magazines, but the number of publications is the same as that in Asia; the time interval gap of publications in America is earlier than that in Asia, and America's robustness is higher than that in Asia. The quality and quantity of articles published in Oceania and Africa are low, and the scope of research is narrow. All continents need to expand sustainability research fields related to the construction industry and increase cooperation and cross-regional research, so countries in the world should achieve SD research through close collaboration.

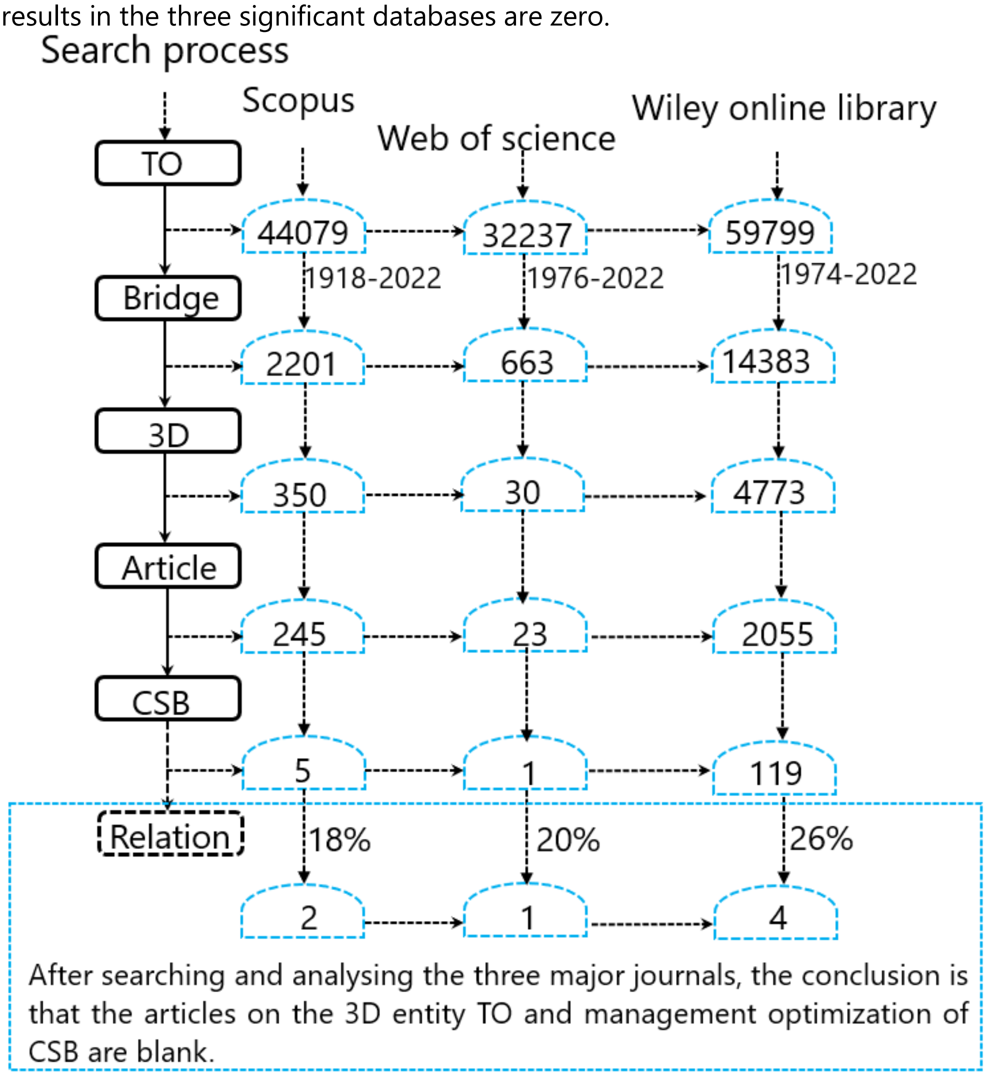
The search keywords in the literature survey in Section 2.2 are Sustainable development, Bridge, and Article. Now the scope of the search keywords is defined as:

a) Sustainable development; Management; Bridge. The search results in the three significant databases of WoS, Scopus, and Wiley online library are zero.

b) Sustainable development; Management; Finite element; Bridge. The search results in the three major databases are zero.

c) Sustainable development; Management; Finite element; Optimization. The search results in the three major databases are zero.

d) Sustainable development; Management; Optimization; Bridge. The search results in the three significant databases are zero.



Notes: After investigating the WOS, Scopus, and Wiley online library, 136,115 documents with a time interval of 105 years were obtained. Similar to CSBs, there is no research achievement in 3D entity TO and management optimization (Figure 2.2) The average approximation law in the existing literature is less than 21.3%.

Figure 2.22. Search processes and data

Sources: Own elaboration, based on part of data from Scopus, WoS and Wiley online library analysis.

According to the above literature survey conclusions, it can be concluded that there is a blank in the research field of Sustainable development, Management; Finite elements; Optimization, and Bridge. Global research in this field is weak and needs many research supplements. It is necessary to strengthen sustainable research on bridges further. The massive loss of fossil energy in buildings is still the core factor affecting the environment and communities.

Chapter 3. Methodology of sustainable assessment

Based on the Millennium Development Goals established in 2000, the United Nations put forward the Sustainable Development Goals (SDGs) in 2015 to address health, social equity and justice, economic security, education, and the environment. Adopted by the international community on January 1, 2016, The accreditation of each member state is officially implemented. The SDG has formulated 17 broad and 169 specific goals as sustainability measures for relevant sectors worldwide (Sullivan et al., 2018).

The author analyzes the published literature and selects the WoS as the survey resource database to study bridge sustainability-related research's theoretical model and system framework. The keywords are sustainable development, bridge; method; paper. A total of 260 articles were retrieved (from 2005 to 2022) (Table 3.1).

According to the content analysis of the retrieved articles, 21 articles are related to the sustainable development of the construction industry. The main applied research models are questionnaire survey, case analysis, literature review; experimental research and statistical data analysis; multi-objective optimization; Mathematical models, and AHP. The systematic assessment and analysis of the sustainable development of bridges (cable-stayed bridges) is insufficient and needs to be supplemented and explained systematically.

For the theoretical system of SD, the published literature is first searched through keywords of sustainable, bridge, theoretical, system, article and review, and a total of 2,496 articles are retrieved, with a time interval of 1977- 2022. Citespace software is used for cluster analysis, and clustering results are obtained according to the two analysis models of keywords & institutions, and countries.

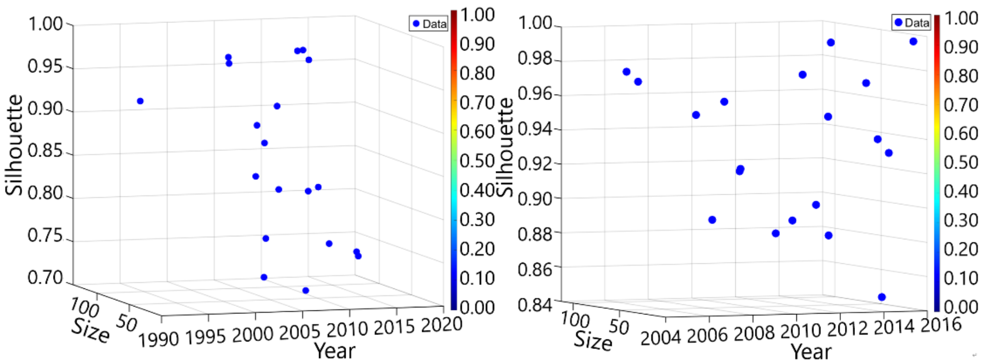
Table 3.1. A theoretical analysis of representative literature

Journal	Methods	Ref
Sustainable Development in Construction	The article evaluates the effectiveness of Indonesia's infrastructure sustainability regulations - a questionnaire for practitioners in the construction industry.	Willar et al., 2019
Mathematics	Article Establishing an International Framework for Engineering Sustainable Project Management - Literature Review (Visual Cluster Analysis), Mathematical Programming Algorithms and Case Studies.	Zhou et al., 2021
Journal of Bridge Engineering	Sustainable design for bridge construction - bridge case studies.	Yen et al., 2014
Sustainability	Bridge Sustainable Construction Management - Multiple Regression Analysis and Loss Estimation Model.	Kim Myong et al., 2020
Sustainable Cities and Society	Smart City Sustainability Project - exploratory case study approach.	Duvier et al., 2018
Construction and Building Materials	Bridge construction technology optimization - Experimental study.	Herrero et al., 2018
Sustainability	Suspension bridge tower anchor technology - establishing a sustainable assessment method for bridge construction technology.	Wang et al., 2020
Arabian Journal for Science and Engineering	Sustainability of concrete mixes - case studies and analysis of literature data.	Aydin et al., 2021
Materials and Structures	Sustainable Design Prediction of Long-Span Bridges - Statistical Fit Analysis of Laboratory Data.	Roman et al., 2015
Structure and Infrastructure Engineering	Environmental impact of bridges of different materials - Improved life cycle assessment and reliability assessment.	Wang et al., 2018
Journal of Cleaner Production	High performance concrete hybrid design - Laboratory optimal design.	Sun et al., 2021

Sustainability	Establishment of civil infrastructure evaluation system-two-frame theory and multi-attribute value theory.	Liu et al., 2021
Sustainability	Progressive failure of frame structures - numerical model verification analysis.	Li et al., 2019
Materials	Overall structural performance evaluation of bridges-advanced hybrid algorithm.	Renkas et al., 2021
Structure and Infrastructure Engineering	Life cycle assessment of railway bridge infrastructure - a literature survey method.	Guangli Du & Raid Karoumi., 2012
Renewable and Sustainable Energy Reviews	Adaptation of bridge design to carbon intensity targets - new sustainable designs for large data sets.	Liu et al., 2022
Baltic journal of road and bridge engineering	Bridge design and renovation to reduce life cycle cost-mathematical model calculation.	Beran et al., 2016
Structure and Infrastructure Engineering	Bridge maintenance strategy optimization-multi-dimensional preference analysis decision algorithm based on fuzzy analytic hierarchy process and linear programming technology.	Peng et al., 2020
Sustainability	Continuous evaluation of bridge reliability - establishment of reliability evaluation index system.	Xu et al., 2022
GIScience & Remote Sensing	Land dynamic impact of bridge infrastructure on surrounding urban agglomerations - Forest method and data acquisition preprocessing analysis.	Chu et al., 2021
Journal of Construction Engineering and Management	Bridge management system sustainable resource system amazement - Discrete simulation model; Alternative machine learning model; multi-objective differential evolutionary optimization model.	Abdelkader et al., 2021

Sources: Own elaboration, based on data from WoS.

The keyword clustering network map shows that SD-related research literature is mainly concentrated in the time zone from 2004 to 2014 (Figure 3.1-a), and the keyword with the highest frequency is life cycle; construction industry SD. Sustainable supply chain management; sustainable management-conceptual framework; green bridge environment; sustainable future; natural resource management; environmental management; sustainable work practice. Sustainable landscape management; SD; urban planning; urban sustainability; ecosystem approaches; integrating environment; SD goal-SD; social sustainability; environmental variability; human environment;agro-environmental application; measuring corporate sustainability; global environmental change; air pollution; cryogenic environment; ecological economics; biotic resource;future projection.



(a) (b)

Figure 3.1. Data fitting. (a) Keyword cluster analysis. (b) Cluster analysis of scientific research institutions and countries.

Sources: Own elaboration.

In terms of keyword judgment, the theoretical basis of the published literature is mainly in the three fields of "Environment - Ecosystem – Sustainability." The research institutions and countries are selected as the clustering classification standards, and the keywords associated with the theoretical system and methods of research are obtained through the network map analysis: multiple attribute decision analysis; integrated approach;case study; model-based research; system-based decision support; practical application; rational design; hybrid recovery strategy; web-based multiple criteria decision analysis; sustainable procedure framework; socio-economical spatial morphology dual-keyapproach; multi-criteria sorting method; bioinspired approach; critical review;harvesting technologies-integrative literature review; an exploratory

Table 3.2. A theoretical survey of representative literature

Ref.	Journal	Research methodology	
Wang et al., 2020	Sustainable and Resilient Infrastructure	$C_{DIR}=C_T+C_{PM}+C_{INS}+C_{REP}+C_F+C_D$; $LCC=C_E+C_{DIR}$	Where C_T is the initial costs, C_{PM} is the expected costs of routine preventive maintenance, C_{INS} is the expected costs of inspections, C_{REP} is the expected costs of repair, C_F is the expected failure cost, C_D is the expected demolition costs, C_E is environmental costs, C_{DIR} is engineering costs.
Yang et al., 2020	Structures	$C_{LCC}=C_D+C_{ini}+C_{main}$	C_{LCC} are the life cycle costs, C_D is the design costs, C_{ini} is the initial construction costs, $C_{main}$is the maintenance costs.
Almeida et al., 2015	Structure and Infrastructure Engineering	$CCV_{ACB}=\sum_{p=1}^{np}\left[\sum_{t=0}^{tu}\left(\frac{CD_{p.t.a}+CI_{p.t.a}}{(1+TA)^t}\right)+\frac{CR_p}{(1+TA)^{tu}}\right]$	ACB is all considered bridges, CD, CI and CR are the direct, indirect, and residual costs.
Beran et al., 2016	The Baltic Journal of Road and Bridge Engineering	$LCC=I+r+R_e-R_s+D+E+W+M+O$	LCC is total life-cycle costs, I is initial investment costs, r is interest paid on the loan amount used to purchase the building, R_e is replacement costs, R_s is resale or salvage value, D is disposal costs to remove the structure, E is estimated energy costs, W is estimated water costs, M is estimated maintenance, repair, and upkeep costs, O is estimated other costs associated with ownership.
Lee et al., 2006	Journal of Constructional Steel Research	$E[C_T(X)]=C_I(X)+E[C_M^L(X)]+\sum_{K=1}^{K}E\left[C_{FS_K}^L(X)\right]$	$E[C_T(X)]$ is the total expected LCC and X is a function of design variable, C_I is the discounted life-cycle maintenance costs, $E[C_{FS_K}^L]$ is the expected rehabilitation costs.
Yanaka et al., 2016	Structural concretes	$LCC(t)=C_D+C_I+C_{QA}+C_{IN}(t)+\sum_{i=1}^{M}C_M(t)+P_{F_I}C_{F_I}$	C_D is design costs, C_I is initial costs the construction costs, C_{QA} is expected costs of quality assurance, $C_M(t)$ is expected costs of maintenance, $C_{IN}(t)$ is costs of inspections, M is number of maintenance operations, $P_{F_I}C_{F_I}$ is cumulative probability of failure for each limit state.
Liu et al., 2021	Coatings	$LCC_m=C_C+C_m-C_r+C_{lost}$	LCC_m is represents the manager costs, C_C is represents the construction costs, C_m is represents the maintenance costs, C_r is represents the residual value, C_{lost} is represents the indirect losses.
Brühwiler & Adey, 2005	Structure and Infrastructure Engineering	$C_{tot}=C_{fail}+C_{int}+C_{ser}$	C_{tot} are the total expected costs, C_{fail} is the failure costs of bridge, C_{int} is the intervention costs of bridge, C_{ser} is the serviceability costs of the bridge.
Heitel et al., 2008	Bautechnik	$LCC=I+\sum_{t=1}^{n}\frac{U_t}{(1+i)^t}+\frac{A}{(1+i)^n}$	I are investment costs, U_t is maintenance costs in year, A is demolition costs, n is useful life, u is annual maintenance costs, i is discount rate.
Lee Kelly et al., 2019	American Society of Civil Engineers	$LCC_{NC}=C_i+C_{cm}+C_o+C_mP_m+C_rP_R+C_{cc}P_{cc}+C_uP_u-SV$	C_i、C_{cm}、$C_o$is initial, construction, operation costs. maintenance, C_mP_m、C_rP_R、$C_{cc}P_{cc}$、C_uP_u is replacement, cost of capital, and user costs and their respective probabilities of occurrence，SV is salvage value of the structure.

Sources: Own elaboration, based on data from WoS.

Figure 3.2. The SD under the UN 2030 agenda.

Sources: Based on data from (Fu et al., 2022).

study. The analysis of time zone nodes shows discreteness, which is basically concentrated from 2008 to 2016 (Figure 3.1-b).

The theoretical model of this thesis is established according to the *ISO* theoretical framework paradigm, which is divided into LCC, LSA, and SIA, and finally forms the academic system of evaluation of bridge SD. The influencing factors of each pillar are selected from the 17 goals and 169 targets defined in the 2015 Paris Agreement (*COP21*)and the UN resolution "Changing Our World: 2030 Agenda for SD" (Figure 3.2), focusing on supporting the five core pillars (earth, people, peace, prosperity, and partnership) (Fu et al., 2022).

3.1. Establish life cycle cost theory system

ISO15686-5 stipulates that LCC in the construction industry is the sum of costs incurred in different cycle stages, divided into costs of construction, service, occupation, maintenance, and end of life. The discounted present value is introduced to consider the time value of money (Lu et al., 2021). In this thesis, the LCC-related theoretical system is searched, finding that the research model is usually established according to the five stages of the construction project, and more researchers pay more attention to the cost of the construction stage (which is the core of LCC research). Therefore, we need to focus on the maintenance and deterioration model because the external environment (natural and human environment) is a random event for bridge wear, aging, and deterioration, which seriously affects the service life of the bridge (Table 3.2). In addition, the sensitive impact on damage and maintenance costs is also a focus of this thesis.

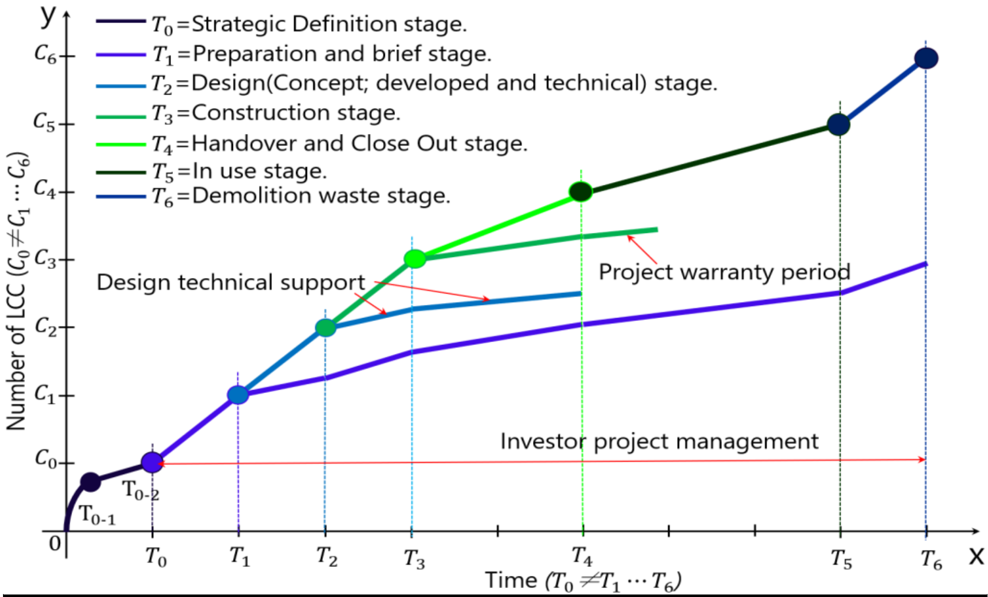
3.1.1. Definition of goal and scope

LCC's research objective is to determine the economic cost of buildings to quantify the overall investment of specific projects and formulate the life strategy of the system.

Its purpose is to minimize the lifetime cost of the project. The research framework is further deepened based on the *ISO* framework. From Figure 3.3, it can be seen that LCC is divided into six stages, of which the investor T_1 participates in the whole life cycle of the project. T_2 is the technical service support and guarantee provided by the design unit to the constructor and the investor during the construction period. The interval is extended to T_4. It will enter the project warranty opreation stage after the constructor T_3 completes the complete acceptance and trial operation of the project, and the construction tasks shall be completed after the warranty period agreed in the construction contract.

3.1.2. Inventory analysis

The research framework of this thesis is implemented according to the standards of *ISO* and SETAC, and the stage data in LCC Analysis are collected according to design drawings and the construction laws and regulations in the area where the case is located. The ecoinventines the quality of research conclusions. Due to the continuous change in the wordwide industry supply chain, database updating and data collection must be conducted synchronously in the front and back-end systems. Ecoinvect completes the increase of the data set and the direct docking of the supply chain and realizes the systematic change of network structure (Steubing et al., 2016). The highway bridge structure in China is selected as the research case. LCC analysis methods and data collection are implemented following the *Preparation Method of Budgetary Estimate and Budget for Highway Engineering Capital Construction Projects* (*JTGB06-2007*), *Approximate Estimate Norm of Highway Project* (*JTG/T3831-2018*).



Code	Instruction	Control elements	References
$T_{0\text{-}1}$	Identify the strategic requirements and core interests of the funder.	Compliance with laws and regulations, customer requirements, sustainability.	Langston et al., 2008
$T_{0\text{-}2}$	Quantitative management.	A high-quality work environment to support core business activities	Shah Ali et al., 2008
T_1	Feasibility study preparation and preliminary engineering.	Develop project feasibility analysis and determine safety, quality, sustainability goals, project budget, and other parameters.	W.M. Chan et al., 2014
T_2	Ensure the health and safety, accessibility, space arrangement and maintenance.	Including outline proposals for structural design, structural design, building services systems, outline specifications, cost information and project strategies.	Amiri et al., 2020
T_3	Complete the project construction in accordance with the design documents.	Off-site manufacturing and on-site construction are carried out according to the construction plan.	Hosny et al., 2018
T_4	The handover of the project and the performance of the construction contract are completed.	Facility, equipment, and systems perform operations and successfully operate maintenance work.	Wang et al., 2013
T_5	System operation, maintenance, service management and supply chain management.	Undertake in-service services, utilize building services, maintain, and review building performance.	Yik et al., 2010
T_6	Handling construction and demolition waste.	The waste is downcycled and used as aggregate in new materials, reducing impact and saving resources.	Di Maria et al., 2018

Figure 3.3. The goals and scope of LCC.

Sources: Own elaboration, based on part of data from WoS.

Cost Quota of Highway Engineering Machinery Shift (*JTG/T3833-2018*) promulgated by Ministry of Transport of the People's Republic of China and bridge design and construction drawings (Chen et al., 2021).

3.1.3. Functional unit

LCC in this thesis is the economic cost analysis of "from cradle to gate". All inputs and outputs of the process involved in the inventory analysis will be identified and quantified. The inventory data will be collected directly from the design documents and engineering-related documents according to the actual project to improve the research's accuracy and authenticity. In view of its particularity, LCC is analyzed as an independent evaluation unit – an overall evaluation of the case bridge.

3.1.4. Mathematical model

Table 3.1 is the classical theoretical model of LCC research, representing the evaluation model paradigm of the currently published literature. Due to the particularity of selected cases and the evaluation data requirements, Table 3.1 is combined with the regional budget method of the chance to establish the LCC theoretical model (ZhiWu Zhou et al., 2020).

Eq.3.1 $$C_M = C_P + C_D + C_C + C_U + C_d$$

C_M = LCC economic cost (CNY); C_P = Cost at preparation stage (CNY); C_D = Cost at design stage (CNY); C_C = Cost at construction stage (CNY); C_U = Maintenance and service cost at use stage (CNY); C_d = Demolition and clean-up stage (CNY).

3.1.4.1.The theoretical model system of China's investment budget

Eq.3.2 $$C_M^E = \sum_{T_0}^{T_6} C_N + \sum_{T_0}^{T_4} C_D + \sum_{T_3}^{T_6} C_O + \sum_{T_0}^{T_4} C_P + \sum_{T_1}^{T_4} C_L$$

C_M^E = Total investment amount (CNY); $\sum_{T_0}^{T_6} C_N$ = CN costs(CNY), CN = Construction and installation costs; $\sum_{T_0}^{T_4} C_D$ = CLD costs (CNY), *CLD* = Compensation for land use and demolition; $\sum_{T_3}^{T_6} C_O$ = OCE costs (CNY), *OCE* = Other costs of engineering construction; $\sum_{T_0}^{T_4} C_P$ = PE cost (CNY), PE = Preparatory expenses; $\sum_{T_1}^{T_4} C_L$ = Loan interest during the construction period. $T_0, \cdots, T_6$ see Figure 3.3.

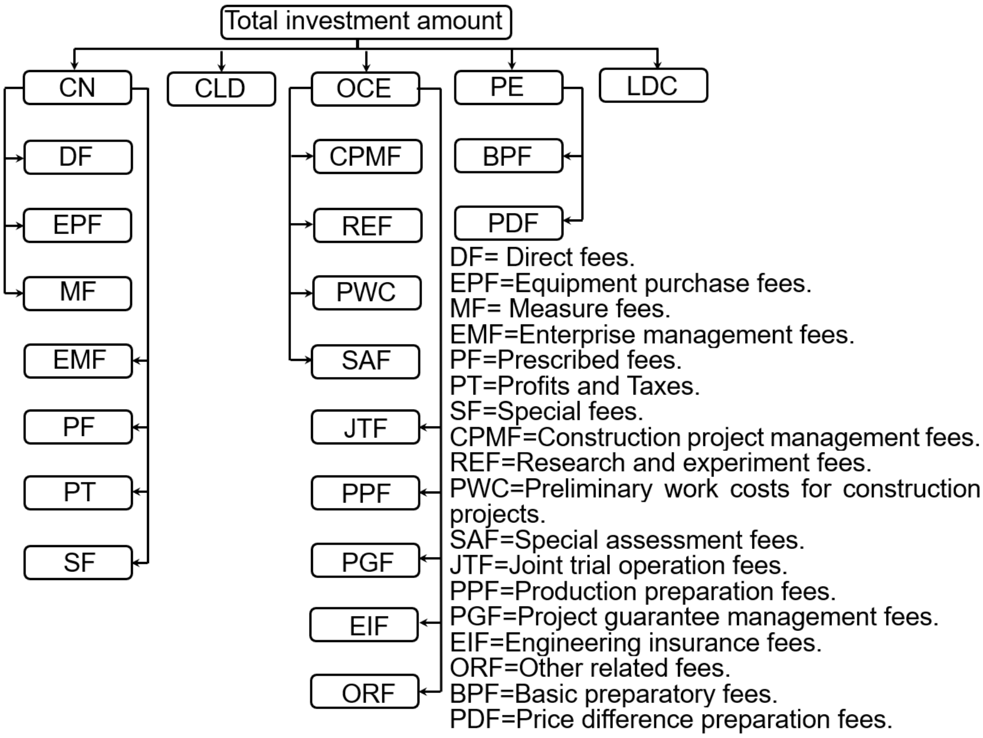


Figure 3.4. LCC theoretical model framework system.

Sources: Own elaboration.

Figure 3.4 is the theoretical framework system of investment estimation of China's highway engineering. Among them, direct cost refers to the expenses that constitute the project entity and contribute to the formation of the project in the construction process; measure price refers to the additional cost of the project (caused by natural factors or special requirements). Enterprise management cost consists of essential expenses, staff expenses, etc.; specified price refers to the costs construction enterprises must pay following laws, regulations, and rules. Special cost includes construction site cost and safety production cost; construction project management cost consists of the costs related to the formalities handled by the investor and the government (Chen et al., 2021). All the case studies use the above cost estimation system for research and analysis. The cost details have been considered in the data analysis without a detailed introduction. The total cost is subject to the quantities provided in the design drawings.

3.1.4.2. Random coupling model

The accumulated random damage caused by sudden events and gradual structure deterioration is an inevitable problem in the maintenance and opreation stage; its probability distribution is also critical to the sensitivity of cost (Sanchez-Silva et al., 2012). This problem can be solved by the combined time-dependent performance probability model of structural components.

Therefore, a structural damage cost C_d is introduced. After the discrete random event, the structural components will be damaged, and its maintenance cost is included in the maintenance stage and not calculated separately (Sanchez-Silva et al., 2012).

Eq.3.3 $$C_d(M,T) = \int_{T_4}^{T_5} \int_0^{n_d} C_d(M,Z,T)\, dH(M,Z)$$

$C_d(M,T)$ refers to the cost incurred due to damage P in time range T (CNY); the probability distribution of $T \in (T_4, T_5)$ and Z (M) determines the frequency of random time. In order to clearly define the value of C_d, the discrete range is calibrated; n_d is the number of random events.

Eq.3.4 $$C_d(P,T)^R = \begin{Bmatrix} C_d(M,T) & C_d(M,T)^R < 0 \\ C_d(M,T)^R & 0 < C_d(M,T)^R < \sum_{T_2}^{T_3} C_{CN} \\ C_I & \sum_{T_2}^{T_3} C_{CN} < C_d(M,T)^R \\ C_R & \sum_{T_2}^{T_3} C_{CN} << C_d(M,T)^R \end{Bmatrix}$$

$C_d(M,T)^R$ is the discrete cost included in C_M^E (CNY); $\sum_{T_2}^{T_3} C_{CN}$ is the original cost incurred in the interval of $T \in (T_2, T_3)$ (CNY); C_I is calculation of incurring cost (CNY); C_R is cost of re-budget (CNY).

Combining the above mathematical model system, we finally get:

Eq.3.5 $$C_M^N = \begin{Bmatrix} C_M + C_d(M,T)^R & \text{Classical theoretical models} \\ C_M^E \pm C_d(M,T)^R & \text{China theoretical models} \end{Bmatrix}$$

C_M^N is the final LCC economic cost (CNY).

3.2. Establish life cycle assessment theory system

In the LCA literature, researchers have proposed five uncertain factors: inaccuracy, incompleteness, obsolescence or data missing, the uncertainty of the model, and uncertainty caused by the research process (Y.-R. Zhang et al., 2016). Affected by the above factors, the following control points are formulated to improve the robustness of the research conclusions:

a) The establishment of the investigation model framework system - the investigation is carried out based on *ISO14040~14044*, because it is the most internationally recognized, widely used, and mature framework globally.

b) The database selection - this is the key to determining LCA analysis. Selecting a high-quality database system that updates synchronously with the production network system of the times can obtain the more scientific and robust research.

c) The use and selection of research tools - LCA is used in a broad field, and various indicators have been expanded to "variability and diversification." The research results of mature software are much higher than those of the questionnaire survey, influencing factor citation evaluation, and other research models, but only powerful and flexible software system modeling research can realize open data integration and analysis.

d) The sensitivity analysis of key impact indicators and evaluation outcome it is used to decide the influence of parameters on the overall results and discretize the interference of highly uncertain factors to improve the robustness of the comprehensive research.

3.2.1. Concept of goal and scope

The research subject of this thesis is the super sizeable CSB composite system of the expressway, which has great difficulty and enormous research scope, due to the continuous innovation of engineering structure design concepts and the improvement of satisfaction standards. This study tends toward comfort, aesthetics, and ecological needs based on meeting the original low-cost, safety, and quality, resulting in earth-shaking changes in the performance indicators of conceptual design (Biondini & Marchiondelli, 2008), increasing the SD control difficulty. Selecting the super central bridge with an abnormally complex structure as the research model can obtain a comprehensive analysis result and lay a quantitative foundation for the accurate numerical model, which is more challenging for the SD research on the bridge.

The study is divided into five stages according to the *ISO* framework: Material production stage, Design stage, Construction stage, Use stage and Demolition stage. The research case is a Chinese bridge built according to *JTG/TD65-01-2007* and *General Code for Design of JTGD60-2015* promulgated by the Ministry of Transport of China. It meets safety, durability, applicability, environmental protection, economy, and aesthetics (Xie et al., 2018). The design reference period of the highway bridge structure is 100 years, and that of stay cable is 20 years.

Figure 3.5 is the theoretical framework, and the research software is OpenLCA1.10, which is widely used in Europe, the United States, and Japan. Research indicators have been expanded, and "diversification" from CO_2 to global warming potential to complete LCA, including 15 different social and economic impacts categories. The software is characterized by a vast system and database processing capacity. GIS integration function, fast and flexible interface, parameters and characterization factors uncertainty processing, and robust database support (23 databases are connected with the standard software system to complete direct import and format conversion). The common software includes Ecoinvent, JRC European Commission, Idemat, Agri-footprint, Psilca, Probas Soca, and Arvi (Pons et al., 2018).

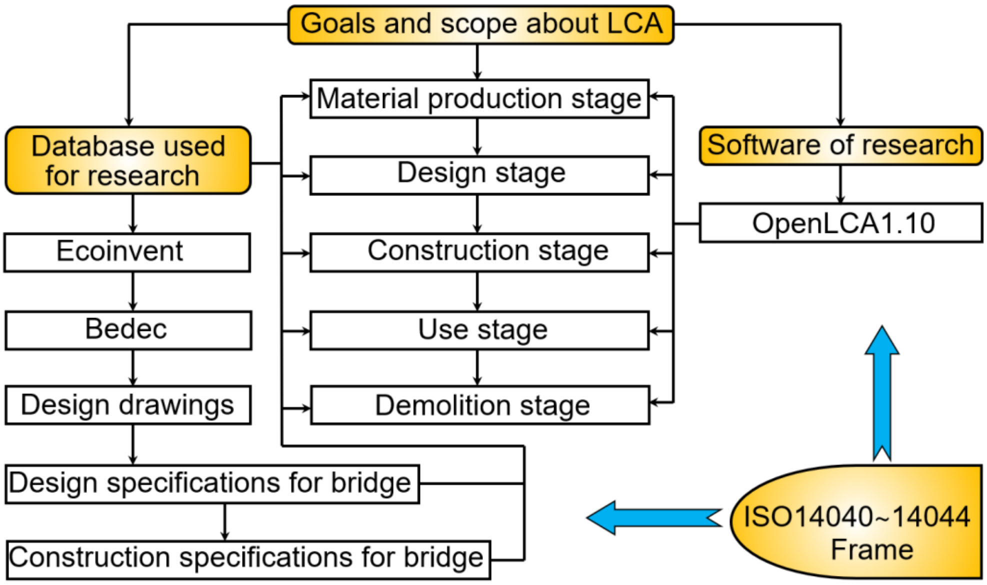


Figure 3.5. Goals and scope of LCA.

Sources: Own elaboration.

3.2.2. Analysis of basic concepts

The environmental contribution of the CSB is a systematic influence process from the cradle to the grave. All the processes of each stage are used as LCA data input, and the emissions of the process to the environment are used as output data. There are relevant instructions in an international standard (*ISO-2006b*). Determine the environmental time dimension according to local laws and regulations and design drawings, including demolition to landfill and transportation of waste.

The model framework is established according to *ISO*, SETAC, and EDIP requirements. According to the model, ten impact categories are selected as the analysis objects, laying a robust foundation for the research, see Table 3.2. Scientists use midpoint and endpoint modeling in their LCA modeling analysis. Midpoint modeling is applied to specific location indicators, and Its disadvantage is uncertainty about the expected duration and model. Endpoint modeling includes the entire environmental mechanism and quantitative modeling; the disadvantage is that there are many uncertainties and unknown factors (Finnveden et al., 2009).

After comparing the advantages and disadvantages of the two methods, it is determined that two standard modeling methods of midpoint and end point are adopted in the modeling analysis of CSB, and weighting parameters are introduced in the LCA modeling process.

3.2.3. Functional unit

The CSB structure is highly statically indeterminate, and the component shows nonlinear behavior. Due to the complexity and variable cross-section of the modeling, it isn't easy to be used as a research unit. m^2、 m^3 selecting the weight as the functional unit can meet the needs of the LCA research. Kg.

The input of each index is all classified as quality-related variable parameters, and the estimated cost of the fixed cost is added. The conclusions of the analysis data are traceable and scientific.

3.2.4. Mathematical model

Zhou et al. (2020) introduced OpenLCA1.10 series software in many studies to analyze the contribution of Chinese CSBs to environmental, economic, and social impact. They established a complete assessment framework and modeling theory, contributing to project management mode and complex network mathematical model innovation. The LCA theoretical model of this thesis is based on the relevant published academic system.

3.2.4.1. Material production stage

Materials are an essential part of any structure and the primary source of non-renewable resources and energy consumption. For new projects, the impact must be considered and assessed to reduce consumption, including utilizing of environmental protection materials, composite materials, design optimization, improvement of construction efficiency, and an advanced project management model. Key impacts to be noted at this stage include necessary asset information, accurate material quantity, and construction process, familiar with raw material production process and extracted material environment data (Jena & Kaewunruen, 2021).

Eq.3.6 $M_L = \sum_{T_0}^{T_1}\{[M_n \times (1 \pm \mu_c)] \times \lambda_c +, \cdots, +[M_m \times (1 \pm \mu_d)] \times \lambda_d\}$

M_L is material LCA impact data (kg); M_n and M_m are the weights of n-m kinds of different materials (kg); μ_c and μ_d are the material production process loss rate (%); λ_c and λ_d are the material coefficient affecting the emission (kg/kg); see Figure 3.3 for T_0 and T_1.

3.2.4.2. Design stage

Good design is a critical way to reduce environmental impact and energy consumption, and the optimized design scheme determines the sustainable impact of the project. Designers should be responsible for choosing innovative and environmentally friendly material solutions. The key to improving energy-saving design is the supply of diverse green systems, green technologies, and sustainability analysis (De Masi et al., 2019).

Eq.3.7 $D_L = \sum_{T_2}^{T_4}\{P_n \times \lambda_p + [M_d \times (1 \pm \mu_u)] \times \lambda_c + M_l \times \lambda_m\} \times (1 \pm \sum M_O)$

D_L is LCA impact data at the design stage (kg); P_n is the number of relevant design personnel (person-day); M_d is the number of materials in the design consumed and used (kg); μ_u is the material wastage rate in the design (%); M_l is the loss of relevant equipment and oil used at the design stage (kg); λ_p and λ_m are the emission coefficient of the environmental impact of personnel and equipment (kg/kg); $\sum M_O$ is the design optimization rate (%, analyzed in Chapter IV); see Figure 3.3 for T_2 and T_4.

3.2.4.3. Construction stage

Concrete and steel are the primary building materials for bridges. Typical LCA at the construction stage includes the procurement of raw materials, production, transportation, construction of concrete and structural components, and treatment of labor, equipment, and waste during construction (Hájek et al., 2011).

Eq.3.8 $$C_L = \sum_{T_3}^{T_5}\left\{(P_c \times \lambda_p) + \left[[M_c^{1,2} \times (1 \pm \mu_b)] \times \lambda_c\right] + M_c^{1,2} \times \lambda_m\right\}$$

C_L is the impact data at the construction stage (kg); P_c is the number of personnel at the construction and quality assurance stage (person-day); M_c^1 is the quantity of other materials (excluding materials outside the scope of design drawings) during construction (kg); μ_b is the loss rate during construction (%); M_c^2 is the amount of energy consumed by machinery and equipment used in construction (kg); see Figure 3.3 for T_3 and T_5.

Eq.3.9 $$C_L^T = C_{LCA} \times (1 \pm \mu_m)$$

C_L^T is the impact data at the final construction stage (kg); μ_m is the reduction rate of project management model after using optimized management (%, analyzed in Chapter IV).

3.2.4.4. Use stage

The deterioration of transport infrastructure is one of the leading transport challenges faced by countries face worldwide. Structural aging, especially in bridge structures, is caused by the rapid increase in the number of vehicles, the increase in frequency and intensity caused by climate change, environmental pressure (acidification and corrosion), and long-term effects (structural shrinkage, fatigue, and creep) (D. Y. Yang & Frangopol, 2020).

The optimal bridge maintenance plan determines the contribution of LCA data. Most maintenance management frameworks are established based on metaheuristic optimization technology, general algorithm, particle swarm optimization, AI technology, swarm network technology, harmonious search, and simulation degradation methods (García-Segura et al., 2017). The determinants include material durability, structural service life, design, installation quality, expected maintenance scheme, climate, and exposure to natural variables. The objectives and boundaries of sustainable maintenance include accuracy, instantaneity, environmental protection, cost-saving, and resource efficiency improvement of the maintenance stage (Carlson & Sakao, 2020).

Eq.3.10 $$U_L = \int_{T_4}^{T_5} \frac{dU_c(C_t)}{d(C_t)} \cdot p|C_t| \cdot dC_t \times \left[1 \pm \int T_i\left(N_a,\ E_a, \cdots, F_a\right) dT_i\right]$$

U_L is the impact data at the final use stage (kg); U_C is the maintenance cycle (T); C_t is the maintenance cost (CNY); T_i is the number of maintenance due to uncertain factors; N_a is unnatural damage; E_a is earthquake disaster; F_a is a traffic accident.

3.2.4.5. Demolition stage

The EU implements a high-quality management mode of selective demolition and recycling of waste according to the circular economy principle. The system boundary includes all activities in the life cycle of waste management. The recovery rate of concrete is 17% (traditional demolition) and 53% (selective demolition); the power consumption is 0.1KWh/t, and the diesel consumption is 1.8MJ/t (traditional demolition) and 2.8MJ/t (selective demolition) (Iodice et al., 2021).

The recovery rate is very significant for assessing the scrap stage of the building system. The recovery rates of several main materials are as follows: alumina, copper, and zinc > 90%; steel, concrete > 75% (Rixrath & Wartha, 2016).

The waste after the demolition shall be recycled, landfilled, and dumped, and the main steps are as follows: waste collection, classification, transportation, recycling, and final disposal. The overall standard requirement is to quantify and reduce CE and environmental pollution in the demolition cycle.

Eq.3.11 $D_L^d = \sum_{T_5}^{T_6}\{[P_n \times \lambda_p + E_n \times \lambda_e \times (1 \pm \lambda_f)] + M_n \times \lambda_v \times (1 \pm \lambda_t)\}$

D_L^d is the emission at the demolition stage (Kg); P_n is the total number of labor force (person-day); λ_p is the per capita emission coefficient (kg/person-day); E_n is the total energy consumed by equipment and machinery (kg); λ_e is the emission of each energy source (kg); λ_f is the energy loss rate of machinery (%); M_n is the total amount of material used (kg); λ_v is the emission of materials (kg); λ_t is the material wastage rate (%).

The data evaluation at this stage includes the secondary utilization after recycling and processing, and the high recovery rate of steel bars.

3.3. Establish social impact assessment theory system

According to the *ISO14040* and *14044* standard evaluation frameworks, UNEP has formulated the SIA assessment guide and determined the ultimate goal of SIA technology is to "promote the improvement of social conditions and the overall socio-economic performance of all stakeholders. In the whole life cycle of the products." Subcategories involve five categories of stakeholders and 31 impact indicators in the construction, maintenance, transformation, and repair of public facilities. The improper planning, design, or construction (if any) will have a substantial negative impact on society by changing the way of "people's life, work, entertainment, interconnection, and organization to meet people's needs and generally respond as social members" (Gilchrist & Allouche, 2005). For large-scale transportation projects, SIA is more influential and destructive. The key to risk control lies in: project risk control, the impact of community participation, and systematic follow-up balance.

3.3.1. Definition of research content

The research is based on the UNEP/SETAC guide and the *ISO14040* framework. The main driving force of the model is the stakeholders and the value chains committed to various indicators, which comprehensively include five main stakeholder categories: employees/workers, local communities, society (relevant national and global), consumers, and participants in the value chain. The scope of the value chain includes decision-makers of the strategic action results or the management responsible for the decision process, Middle management and experts directly involved in the implementation process and final actions, and the public and individuals affecting the planning and implementation (Climent-Gil et al., 2018). This thesis studies SIA impact, especially the social effects in the bridge area, according to the whole life cycle of the bridge, quantitatively analyzes and identifies the multi-path model with diverse impact categories to reduce and balance the interests of stakeholders to realize the efficiency of SIA. After identifying all possible positive and negative consequences of the expected project on the relevant community or society, this thesis also implements effective mitigation plans to reduce the negative social impact.

3.3.2. Analysis of the current situation

UNEP/SETAC lists the types of influencing factors. There are 31 impact categories related to social interests. The key concerns are Child labor, Health, Safety, Safe and healthy living conditions, Community engagement, Contribution to economic development, Promoting social responsibility, and Cultural heritage (Benoît-Norris et al., 2011). Ramsbottom proposed ten core indicators in the SIA study on infrastructure, including community vitality of the construction project, reduction of the use of non-renewable resources, diversity of communities and employees in the construction project, respecting and caring for the community, changes in attitudes and practices, social sustainability tracking, awareness, global network and organizational responsibility and accountability (Vitorio Junior & Kripka, 2020). In the SIA study on pavement engineering, the researcher identified four stakeholders (Workers, Local communities, Society, and Consumers) and eight subcategories to quantify the comprehensive impact of the project on social indicators (Subedi et al., 2018). This thesis uses PSILCA and

USDA data and SHDB to evaluate the research on sustainable social pillars proposed by ZhiWu Zhou. The PSILCA database continuously updates data resources, traceable source data, and high-quality assessment data. The database is directly linked to SOCA through Green Delta software. Facilitates environmental and social impact assessments and identifies 54 quantitative and qualitative indicators in 18 categories (ZhiWu Zhou et al., 2020). The determination of specific indicators is analyzed in 3.4.

3.3.3. Functional unit

SIA is a chain information system research based on LCA data. According to the particularity of bridge engineering and the discreteness of influencing factors about data. The data unit shall be subject to the unit corresponding to LCA. The quantitative identification shall be carried out again for particular influencing factors.

3.3.4. Mathematical model

Kexian Wu (2022) established hierarchical theoretical framework for SIA of construction projects. Includ SD four main stakeholders (construction personnel, transport users, local communities and public service providers) and quantitatively analyzed the social index framework through the social cost model.

Eq.3.12 $S_S^1 = SC_1 + SC_2 + SC_3 + SC_4 + SC_5 + SC_6 + SC_7 + SC_8 + SC_9 + SC_{10} + SC_{11}$

S_S^1 is SIA impact data (CNY); $SC_1 = SC_{me,con}$ is the medical costs (CNY); $SC_2 = SC_{il,con}$ is the loss in income caused by death and disability (CNY); $SC_3 = SC_{psl,con}$ is the intangible cost related to pain and loss of comfort facilities (CNY); $SC_4 = SC_{pd,tra}$ is the property loss caused by traffic accident (CNY); $SC_5 = SC_{tl}$ is the monetary cost per unit of travel time (CNY); $SC_6 = SC_{op,dt}$ is the additional service cost of the vehicle (CNY); $SC_7 = SC_{br}$ is the loss in business income affected by the construction project (CNY); $SC_8 = SC_{rp}$ is the loss of labor productivity caused by construction noise (CNY); $SC_9 = SC_{hd}$ is the depreciation on properties caused by construction noise (CNY); $SC_{10} = SC_{ad}$ is accident administrative cost (CNY); $SC_{11} = SC_{pr}$ is the loss in parking revenue (CNY).

Ignacio J. Navarro (2018) determined the mathematical model of eight subcategories through a literature summary, and applied weighted aggregation to allocate the index weight of each category, reflecting the relative importance of each activity to SIA. They are calculated as follows:

Eq.3.13 $S_S^2 = X_l^a + X_g^a + X_s^a + X_S^a + X_L^a + X_a^m + X_u^m + X_p^m$

S_S^2 is SIA person impact data (day); X_l^a is local employment data (day); X_g^a is gender discrimination data (day); X_s^a is workers Safety data (day);X_S^a is fair Salary data (day); X_L^a is economic development data (day); X_a^m is accessibility data (day); X_u^m is user's safety data (day); X_p^m is public opinion data (day).

Comparing mathematical models in Eq.3.12 and Eq.3.13, it can be seen that when using different paradigm indicators to measure SIA impact, the economic data analysis is more precise and direct, reflecting the monetary value of social influence. The latter is the complete responsibility of the *ISO* framework model, and the impact indicators are modeled closely around categories. Their common point is the theoretical mathematical model established according to the category indicators of the impact framework and the consideration of the robustness of the impact weight. The research model framework focuses on community impact analysis, which has a guiding role in analyzing the social impact indicators of construction projects.

The research case is China's expressway bridge. Due to the most dynamic, challenging, and complex construction project of the highway, there are many different uncertainties, complexities, and risks, including long construction lines and a wide range of crossing areas, complex geological conditions in planning and design, many field operations in engineering construction, long construction period, many dynamic influencing factors and external interferences, long service time, the significant influence of natural climate and many passing vehicles (Moghayedi & Windapo, 2019). The scale and impact of uncertain factors are different at different stages, so SIA modeling establishes the mathematical model in five steps based on Figure 3.5.

Eq.3.14 $S_S^3=\sum_{T_0}^{T_2}\left[M_S\times\left(1\pm\lambda_j\right)\right]+\sum_{T_2}^{T_3}\left[D_S\times(1\pm\lambda_\alpha)\right]+\sum_{T_3}^{T_4}\left[C_S\times\left(1\pm\lambda_\beta\right)\right]+\sum_{T_4}^{T_5}\left[U_S\times\left(1\pm\lambda_\eta\right)\right]+\sum_{T_5}^{T_6}\left[D_s\times(1\pm\lambda_\varepsilon)\right]$

S_S^3 is the SIA impact data at the material stage; M_S is the impact at the material preparation stage; λ_j is the influence probability of uncertain factors (%); D_S is the impact of design stage (iteration one); λ_α is the influence probability of uncertain factors (%); C_S is the impact of design stage (iteration two); λ_β is the influence probability of uncertain factors (%); U_S is the impact of design stage (iteration three); λ_η is the influence probability of uncertain factors (%); D_s is the impact of design stage (iteration four); λ_ε is the influence probability of uncertain factors (%) (ZhiWu Zhou et al., 2020).

3.4. Determine sustainable development impact parameters

SD research should consider the economy, technology, service, environment, hydrology, society, etc. It is necessary to significantly improve the model's performance to accurately study the parameters and nonlinear characteristics in the model framework (Koc et al., 2021).

3.4.1. Analysis of LCC

In 3.1, we have discussed that the LCC cost in the construction project is divided into five parts: the cost of early-stage, construction, service, maintenance, and disposal, classified as the sub-items of each expenditure, respectively. After determining the above parameters, several key indicators need to be considered (Table 3.2):

a) Residual value: it is not only the assessed value after the welfare reaches its expected life but also the residual incentive after determining the deterioration cost (Shamsuddin et al., 2021).

b) Sensitivity analysis: because of the uncertain factors in the research model, it is necessary to calibrate the monitoring data and qualitatively and quantitatively allocate the variables, so sensitivity analysis should be conducted. This technology falls into two categories: local sensitivity analysis and global sensitivity analysis. The latter is suitable for nonlinear systems. For the research software, Monte Carlo deals with the interference of uncertain factors, and linear regression analysis is selected to construct the sensitivity measurement of elements and models (J. Yang, 2011).

Eq.3.15

$$y_{\upsilon} = b_0 + \sum_{i=1}^{i=n} b_i x_i$$
$$C_i = \left| b_i \frac{\hat{s_i}}{s} \right|$$

The model will output the measure of the sensitivity to factor x_i; y_{υ} is the regression coefficient b_i; $C_i = SRC_i$ is the measure of sensitivity; $\hat{s_i}$ and s are the estimated standard deviation of x_i and y (J. Yang, 2011).

3.4.2. Analysis of LCA

Zhi Wu Zhou (2022) identified five as the primary influence parameter indicators in the LCIA study of China's CSBs in China. TGWP, AEP, PMFP, and SWP, particulate matter formation parameters, and solid waste parameters. For research software, OpenLCA1.10.3, the midpoint model is selected for analysis, and ten indicators can be obtained, which are (Table 3.2): The ten indicators as the bridge structure is mainly made of fossil energy resources, the mining, processing, dust, and metal elements cause severe damage to the environment. The above ten indicators are selected as the data parameters of LCA research.

The recipe is the LCA impact assessment method, which converts emissions and resource extraction into the limited environmental impact data through characterization factors. The main techniques are midpoint level (process) and endpoint level. The midpoint indicator focuses on a single ecological issue; endpoint indicators show environmental impacts at a higher level of aggregation. The two methods are complementary.The midpoint characterization has a stronger relationship with the ecological flow and has low parameter uncertainty; the endpoint characterization is easier to explain by the correlation of environmental discharge. This thesis uses the midpoint and endpoint to complete the analysis (Pang et al., 2015).

3.4.3. Analysis of SIA

SIA research adopts the data from the PSILCA database, which is still one of the most comprehensive social LCA studies published in the world. It provides data from about 15,000 sectors and 189 countries, It can be divided into 88 qualitative and quantitative indicators. The findings are grouped into five stakeholders and 23 sub-categories, namely child labor, forced labor, etc (Balasbaneh et al., 2018).

According to the characteristics of research cases and published literature, ten indicators are selected as the research core of this thesis.The following 37 indicators are used for the comprehensive evaluation (Table 3.3): Corruption, Fatal accidents, Llliteracy, etc (Penadés-Plà et al., 2020).

3.5. Summary of this chapter

This chapter comprehensively describes the theoretical mathematical models of LCC, LCA, and SIA and makes a comparative study and analysis of the selection of model parameters. In the academic stage of the model, the robustness is evaluated, and the paradigm is improved according to the discreteness, complexity, and uncertain factors of the research object. The interferences of natural, human and sudden factors in SA are solved, making the theoretical model system more systematic and mature. Because of the abruptness and sensitivity of different elements in LCC, LCA, and SIA research, the research scope and theoretical approach are defined, laying a solid academic foundation for the case study.

Establish a typical model: a) A damage mathematical model is introduced in LCC to solve the economic assessment of discrete random emergencies. b) A multi-level chain system evaluation framework is established in SIA, and weighted indicators are used to define the sensitivity of parameters.

Table 3.3. Summary of SA impact categories

Type	LCC	LCA	SIA
1	Construction and installation costs	Abiotic depletion	Anti-competitive behaviour or violation of anti-trust and monopoly legislation
2	Compensation for land use and demolition	Acidification	Association and bargaining rights
3	Other costs of engineering construction	Eutrophication	Biomass consumption
4	Preparatory expenses	Fresh water aquatic ecotox	Certified environmental management system
5	Loan interest during the construction period	Global warming (GWP100)	Child Labour, female
6	/	Human toxicity	Child Labour, male
7	/	Marine aquatic ecotoxicity	Child Labour, total
8	/	Ozone layer depletion (ODP)	Corruption
9	/	Photochemical oxidation	Dalys due to indoor and outdoor air and water pollution
10	/	Terrestrial ecotoxicity	Drinking water coverage
11	/	/	Education
12	/	/	Fair Salary
13	/	/	Fatal accidents
14	/	/	Fossil fuel consumption
15	/	/	Frequency of forced labour
16	/	/	Gender wage gap
17	/	/	Goods produced by forced labour
18	/	/	Health expenditure
19	/	/	Illiteracy

20	/	/	Indigenous rights
21	/	/	Industrial water depletion
22	/	/	International migrant stock
23	/	/	International migrant workers (in the sector/ site)
24	/	/	Mineral's consumption
25	/	/	Net migration
26	/	/	Non-fatal accidents
27	/	/	Pollution
28	/	/	Safety measures
29	/	/	Sanitation coverage
30	/	/	Social security expenditures
31	/	/	Trade unionism
32	/	/	Trafficking in persons
33	/	/	Unemployment
34	/	/	Violations of employment laws and regulations
35	/	/	Weekly hours of work per employee
36	/	/	Workers affected by natural disasters
37	/	/	Youth illiteracy

Note: black font is the core influencing factors selected.

Sources: Based on part of data from (Balasbaneh et al., 2018).

Chapter 4. Methodology of topology optimization and management

Optimization is the process of searching for specific problems according to special conditions. It is defined as using all feasible data to find the best value of particular network parameters to maximize or minimize the network target output. Its goal is to find a viable and optimal response. The most commonly used type in works is structural optimization, aiming to find the most suitable arrangement of structures or parts and the best materials for energy conservation and environmental protection. Moreover, structural optimization is divided into four categories: shape optimization, size optimization, TO, and multi-objective optimization (Degertekin, 2012).

Early research mainly calculated the optimization algorithm structure through simple digital programming and mathematical theorem derivation. Still, obtaining the optimal solution for high complexity and high-dimensional problems is challenging with the rapid development of computer science and visual network information technology. Researchers have developed more robust optimization technologies and reproduced the best optimization scheme and conceptual model through numerical simulation, building information models, VI, and 3D technology, realizing the system optimization (Gan et al., 2020).

4.1. Establish sustainable development optimization indicators

The investigation and analysis of the published literature (Table 4.1) show that there is much literature in the theoretical research on structural concrete TO with nonlinear materials in civil engineering, but the number of concrete structures that can genuinely realize TO is minimal (Stoiber & Kromoser, 2021). The reason is that TO is an auxiliary method of structural design. Architects and engineers are more concerned with the constraints imposed in the actual construction, such as design specifications, manufacturability (Kazakis et al., 2017).

Table 4.1. Statistical analysis of existing literature

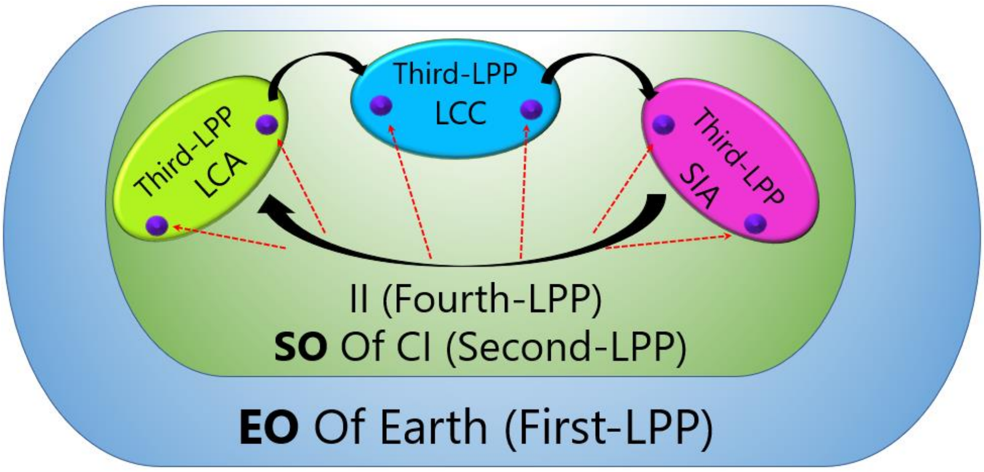
Theoretical framework	Methods and limited	Characteristics	Application
Concept of optimization	Stiffness、weight、instabilities、displacement、economy、environment、functionality、durability and aesthetics.		
Divide of optimization	Size、shape and topology	/	/
TO methods	Optimality criteria	Ground structure method	The layout optimization of truss structures.
		Homogenization method	Finite element mesoscale voids, cavity regions, and material porous structure.
		Solider isotropic material with penalization	The Solid Isotropic Material with Penalization method.
	Heuristic-intuitive		Apply penalty methods to discrete problems and solid isotropic materials.
Solution strategies	Pure mathematical techniques		/
	Stochastic methods	/	/
	Evolutionary algorithms	/	/
	Pure heuristic methods	/	/
	OC methods	Heuristic method Mathematical method	Based on the Karush–Kuhn–Tucker condition.
Nonlinear material behavior	Nonlinear effects	Tension softening Shrinkage Macrocracking	Nonlinear elasticity、theory of plasticity and damage mechanics.

		Compression softening	
		Confinement in compression	
		Reinforcement	
		Strain hardening	
		Yielding	
		Rupture	
		Bucking	
Finite element analysis	Nonlinear material effects	Strain localization	Plain concrete
		Size effect	
Methodology and material	multilateral modeling	multilateral modeling	Steel reinforcement and concrete.
	Stress constraints	Minimum volume	
	Concrete damage	The isotropic damage model	
	Strut and tie modeling	Regions of geometrical or static discontinuities characterized.	
	Combined truss-continuum optimization	The truss-continuum hybrid model.	
	Multiple load cases	A plural number of weighted objective functions.	
	Construction techniques	Manufacturability and layout optimization.	
	Alternative approaches	Aesthetics, manufacturability and architectural design applied toTO.	
Experimental applications	Multilateral modeling	Hybrid concrete-steel truss structure with fiber-reinforced concrete.	
	Stress constraints	Density Optimization Using Stress Constraints.	
	Strut and tie modeling	Steel elements are necessary of the geometry.	
	Combined truss-continuum TO	Promoting hybrid reinforcement concepts.	
	Construction techniques	Post-tensioning reinforcement system.	

Sources: Own elaboration, based on part of data from WoS.

4.1.1. LCC, LCA and SIA optimization concepts

Optimizing the building structure is one of the effective means to reduce LCC. On the premise of ensuring safety, the burden of the system must be reduced in the early design stage to achieve the best performance design scheme and the lowest initial cost. One or more solutions shall be found, during which all constraints shall be considered, and one or more objective functions shall be minimized (or maximized). Optimization techniques depend on two key factors: optimization parameters and search methods. The optimization methods include: Enumerative, systematic, calculus-based or gradient-based, stochastic, random, or gradient-free (Sharif & Hammad, 2019). As a highly complex installation project, bridge engineering involves performance, analysis, monitoring, and other aspects. It is necessary to balance several conflicting objectives and minimize LCC.



Notes:
EO = Ecologically optimization; SD= Sustainable development.
LPP = Life programming and constraint problems.
CI = Construction industry.
II = Impact indicators. Abbreviations only apply to this Figure.

Figure 4.1. Connection of LCC, LCA, SIA and SD.

Sources: Own elaboration.

LCA is a scientific, structured, and comprehensive tool that can effectively quantify the structure's sustainability over time and consider the impact of structural degradation to provide engineers and decision-makers with a complete picture of wise decision-making and system performance (Frangopol et al., 2017). TO can be used to analyze structural optimization under the constraints of stress, displacement, temperature, and other mechanical properties. Its ultimate goal is to achieve functional performance, reduce weight, and prevent the transfer of environmental burden downstream of the product life cycle. Furthermore, it also aims to make maximum use of standard structure modularization and level set parameterization to reduce structural symmetry and repeated model constraints, integrate the optimal design of the structure, and solve the constraints in the irregular domain (P. Wei et al., 2021). The effective combination of the tools created the optimal design of the environmental supply chain network and realized the inventory analysis and environmental impact assessment of products in the system, obtaining the paradigm of ecosystem sustainability.

SIA is the primary tool of environmental sociology to analyze the social impact caused by the project, which is a relatively immature method because it is difficult to define a common standard to measure the complex testing and verification of social influence paths and social problems related to different disciplines and theories. As a result, the research results have uncertainty and transparency. It is necessary to promote further the connection between standardization research and political & social objectives and improve interpretability and applicability through testing and verification (Pollok et al., 2021). Practical solutions include: accurate establishment of the methodological framework; precise identification of social issues; reasonable selection of database; applicable impact categories and assessment criteria; consideration and planning for evaluation of various activities in the whole supply chain, as well as design optimization; Sensitivity analysis is carried out in different stages or in the process of generating weights for activity variables (S. Liu & Qian, 2019). See Figure 4.1 for the robustness of the three methods.

Human existence and development depend on the appropriate environment. SD principle is the harmonious development of economy, society and environment; environmental protection, and economic development; innovation according to local conditions; people-oriented overall planning, and cooperative development (Song, 2011).

4.1.2. Optimization principles of system

Firstly, the variational problem is introduced to deal with the relationship between the controlled objects. Considering that the function of the controlled thing is (Chambers, 1965):

Eq.4.1 $\dot{x} = f(x,u),\ x = (x^1, \cdots, x^n)^T \in R^n, u = (u^1, \cdots, u^r)^T \in U \subset R^r$

The function $f(x,u)$ is smooth; $\dot{x}$ *is variable;* x and u are the function argument; U is the resource set. Let $\Omega_1 \subset R^n$ be the terminal set. According to the optimization law of Lagrange multiplier method, it is necessary to find a control to obtain $x(t_1) \in \Omega_1$ and minimize the integration:

Eq.4.2 $$J = \int_0^{t_1} f^0\,[x(t),u(t)]dt$$

$$\begin{cases} f^0(x,u) = 1, J = t_1 & \min\limits_{t} x_0 \ll \Omega_1 \\ \min\limits_{value} g\big(x(t_1)\big) \subset g(x) & x(t_1) \in \Omega_1 \end{cases}$$

Eq.4.1 and 4.2 are established based on the optimization law of Lagrange multiplier method and the weierstrass theorem. Hestenes deduced the formula of maximum optimization principle (Boltyanski & Poznyak, 1999): After introducing a variable $\Upsilon = (\Upsilon_1,\cdots,\Upsilon_n)$, we can get $H(\Upsilon,x,u) = [\Upsilon, f(x,u)] = \sum\limits_{i=1}^{i=n} \Upsilon_i f^i(x,u)$, J is the biggest optimization value; M_1 is the control variable; $\dot{\Upsilon}_j$ is variable set of multiple constraints; corresponding to the conditional function $x(t)$ and $u(t)$, $0 \le t \le t_1$ of the conjugated system:

Eq.4.3

$$\begin{cases} \dot{\Upsilon} = -\frac{\delta H}{\delta x}, i.e & \dot{\Upsilon}_j = -\frac{\delta H[\Upsilon(t),x(t),u(t)]}{\delta x^j}, j = 1,\cdots,n \\ H[\Upsilon(t),x(t),u(t)] = \max\limits_{u\in U} H[\Upsilon(t),x(t),u] & 0 \le t \le t_1 \\ H[\Upsilon(t),x(t),u(t)] = \text{constant} & 0 \le H(t) \\ \Upsilon(t_1) \perp M_1 & x(t_1)\ \text{of terminal point} \end{cases}$$

An open set can be obtained, U is optimal in the local sense and control (Forman et al., 2020). In modern numerical methods, optimization consists of an objective function and one or more constraints, linking each finite element i to the design variables through the element stiffness matrix based on the iterative variable control of the design variables ρ_i (relative element density).

Eq.4.4 $$\min_{\rho} c(\rho) = u^T K(\rho) u = \sum_{i=1}^{n} u_i^T K_i(\rho_i) u_i \text{ (Minimize structural systems)}$$

$$\begin{cases} \dfrac{V(\rho)}{V_0} \le \beta \\ K(\rho)u = f \\ 0 < \rho_i^L \le \rho_i \le \rho_i^u = 1, i \in [1,n] \end{cases}$$

u is the displacement vector; K is the stiffness matrix; f is the load vector; K_i is the element stiffness matrix of element i; n is the total number of finite elements; ρ is the vector of design variables; $V(\rho)$ is the volume under the design variables; V_0 is ordiary volume; β is the sensitivity constraint; ρ_i^L and ρ_i^u are the lower and upper limits of design variables (Forman et al., 2020).

4.1.3. Optimization method of system

In engineering, structural optimization is a tool to eliminate different constraints and achieve maximum efficiency, Still, it depends on problem objectives, design variables, and conditions to minimize (or maximize) the behavior and geometric constraints of the objective function.

Figure 4.2 shows the structural TO of the objective function. The systematic TO methods mainly include a level set method, solid isotropic material method with compensation, homogenization method, and evolutionary structure optimization method (Zargham et al., 2016). Each method has its application scope and characteristics. Structural optimization focuses on the features of the research object. At present, the second method is commonly used.

Based on the discreteness and high coupling threshold of impact data, a new algorithm is studied and innovated to analyze linear and nonlinear optimization level solutions. From Figure 4.1, it can be seen that the whole ecological impact is divided into four categories: environmental environment system = first level planning factor; SD impact = second level planning factor; LCC, LCA, and SIA = third level planning factor; various influencing factors of LCC, LCA, and SIA = fourth level planning factor (Avraamidou & Pistikopoulos, 2019).

Eq.4.5 $$F_n^{\dagger} = \sum_{T_1=S}^{T_n=F} F_n(x,y) = F_n(x_n,y_n)dt >> \min_{x_n,y_n} F_n(x,y)$$

The optimized Eq of the first level factor is:

$$\min_{x_1,y_1} F_1(x,y) \in F_1(x_1,y_1)dt, x=[x_1^T x_2^T, \cdots, x_n^T]^T,\ y=[y_1^T y_2^T, \cdots, y_n^T]^T, x_1, \cdots, x_n \in R^m, y_1, \cdots, y_n \in\ k^p$$

The optimized Eq of the second level factor is:

$$\min_{x_2,y_2} F_2(x,y) \in F_2(x_2,y_2)dt, x=[x_1^T x_2^T, \cdots, x_n^T]^T,\ y=[y_1^T y_2^T, \cdots, y_n^T]^T, x_1, \cdots, x_n \in R^m, y_1, \cdots, y_n \in\ k^p$$

The optimized Eq of the third level factor is:

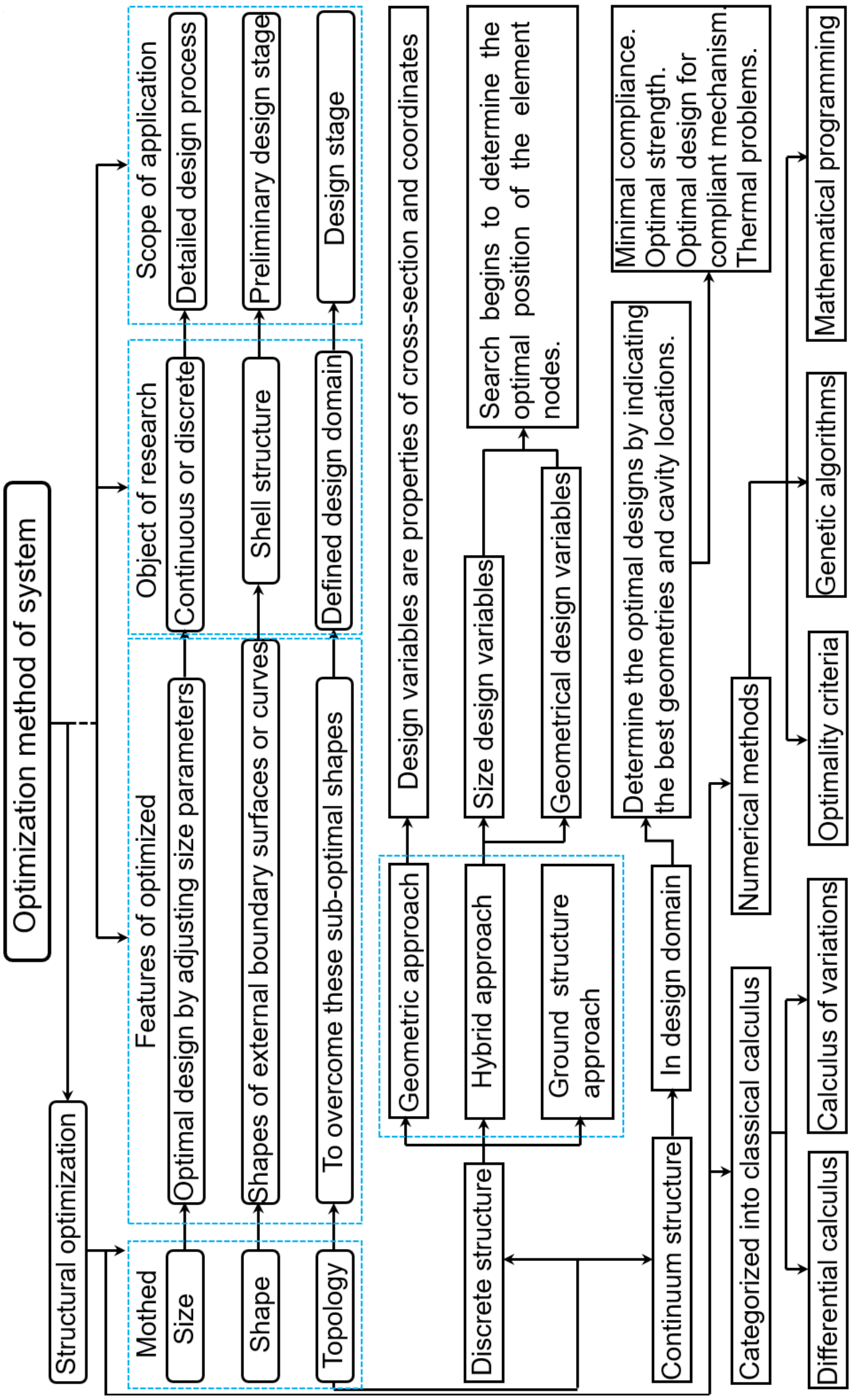
$$\min_{x_3,y_3} F_3(x,y) \in F_3(x_3,y_3)dt, x=[x_1^T x_2^T, \cdots, x_n^T]^T,\ y=[y_1^T y_2^T, \cdots, y_n^T]^T, x_1, \cdots, x_n \in R^m, y_1, \cdots, y_n \in\ k^p$$

The optimized Eq of the fourth level factor is:

$$\min_{x_4,y_4} F_4(x,y) \in F_4(x_4,y_4)dt, x=[x_1^T x_2^T, \cdots, x_n^T]^T,\ y=[y_1^T y_2^T, \cdots, y_n^T]^T, x_1, \cdots, x_n \in R^m, y_1, \cdots, y_n \in\ k^p$$

The optimized Eq of the nth level factor is:

$$\min_{x_n,y_n} F_n(x,y) \in F_n(x_n,y_n)dt, x=[x_1^T x_2^T, \cdots, x_n^T]^T,\ y=[y_1^T y_2^T, \cdots, y_n^T]^T, x_1, \cdots, x_n \in R^m, y_1, \cdots, y_n \in\ k^p$$



Optimization method of system
Structural optimization
Mothed
Size
Shape
Topology
Features of optimized
Optimal design by adjusting size parameters
Shapes of external boundary surfaces or curves
To overcome these sub-optimal shapes
Object of research
Continuous or discrete
Shell structure
Defined design domain
Scope of application
Detailed design process
Preliminary design stage
Design stage
Discrete structure
Geometric approach
Hybrid approach
Ground structure approach
Design variables are properties of cross-section and coordinates
Size design variables
Geometrical design variables
Search begins to determine the optimal position of the element nodes.
Continuum structure
In design domain
Determine the optimal designs by indicating the best geometries and cavity locations.
Minimal compliance.
Optimal strength.
Optimal design for compliant mechanism.
Thermal problems.
Categorized into classical calculus
Numerical methods
Differential calculus
Calculus of variations
Optimality criteria
Genetic algorithms
Mathematical programming

Figure 4.2. Structural optimization system distribution description.

Sources: Own elaboration.

$F_n^{\dagger} = \sum_{T_1=S}^{T_n=F} F_n(x,y)$ is the total data impact of a level in the whole cycle of planning; $F_n(x_n,y_n)dt$ is the influence function in the period with x and y as parameters; $\min_{x_n,y_n} F_n(x,y)$ is the minimum paradigm influence Eq after n times of optimization; x and y are the vectors corresponding to the factor variable; R^m and k^p are sets respectively.

After TO finds the optimal geometry of the structure, the most structural performance data can be captured through the research system, and the parameters should be used to measure the influence of the objective function of each planning stage on the data set of this stage. Based on the improvement of the robustness of the research system, variables need to be introduced to carry out a weighted design for the function of each step (Najafi Moghaddam Gilani et al., 2020). The sensitivity to strain energy needs to be analyzed. The sensitivity of external and internal factors is not distinguished herein, collectively referred to as sensitivity influence.

Eq.4.6

$$\frac{\sigma w_n}{\sigma s_n} = \frac{\max_{F_n} \cup_{x_n}^{y_n} S_n}{\sum_{T_1}^{T_n} (S_1+S_2+,\cdots,+S_n)}$$

$\frac{\sigma w_n}{\sigma s_n}$ is the sensitivity value; $\max_{F_n} \cup_{x_n}^{y_n} S_n$ is the maximum weight of the data set affecting sensitivity in each stage; $\sum_{T_1}^{T_n}(S_1 + S_2+,\cdots,+S_n)$ is the set of sensitivity impact weights in each stage. By introducing the critical load of each increment of Eqs.4.5 and 4.6 into the sensitivity analysis, we can obtain:

Eq.4.7

$$F_x^y = \begin{cases} \min_{x_1,y_1} F_1(x,y) \times \frac{\sigma w_1}{\sigma s_1} & \text{Frist grade} \\ \min_{x_2,y_2} F_2(x,y) \times \frac{\sigma w_2}{\sigma s_2} & \text{Second grade} \\ \min_{x_3,y_3} F_3(x,y) \times \frac{\sigma w_3}{\sigma s_3} & \text{Third grade} \\ \min_{x_n,y_n} F_n(x,y) \times \frac{\sigma w_n}{\sigma s_n} & N\text{th grade} \end{cases}$$

F_x^y is sensitive multi-level planning index parameters; $\frac{\sigma w_1}{\sigma s_1}$ is weight final evaluation index; Eq.4.7 is a multi-level planning index analysis paradigm model considering sensitivity. A new evaluation framework is proposed to solve the discreteness of weight and information and multi-criteria decision-making to improve the impact model's sensitivity and stability in the application. This model can solve the complex situation of wrong structure and make flexible decisions with fuzzy set impact indicators and uncertain data, laying a theoretical method model foundation for benign prediction and analysis (X. Chen & Yang, 2018). This is also a basic mathematical logic theoretical model of TO system research in this thesis.

4.1.4. Optimization system of innovation

The structural system optimization process includes: Structural analysis and modeling; Determination of optimization problems; Optimization methods and technologies; Calculation tools; Design platforms.

Table 4.2. Representative optimization methods for each stage

Optimization system			
References	**Stage**	**Methods**	**Innovation**
Z. Wang et al., 2020	Design	About the formulation of coupled topology and domain shape optimization methods, and demonstrate their main features by illustrating numerical values.	The finite element method formulation of the coupled optimization formula is summarized.
Kandil & El-Rayes, 2006	Construction	The system was developed in four main modules: 1. a multiobjective optimization module; 2. a relational database module; 3. a middleware module;4. a user interface module.	Facilitate the simultaneous optimization of construction time, cost, and quality.
Morcous & Lounis, 2005	Maintenance	To present an approach that uses genetic algorithms in conjunction with Markov-chain models for programming maintenance alternatives.	Enhance the capability and efficiency of the optimization module in the existing infrastructure management systems.
Ghosh et al., 2016	Demolition	A research model is proposed using readily available data such as shipping rates and resale value of recyclable materials to determine research models.	The model will provide an intuitive and simple optimization model while putting the basic principles of reduce, reuse and recycle into action.

Sources: Own elaboration, based on part of data from WoS.

Researchers have developed many optimization methods, such as mathematical programming, numerical search, and the most popular meta-heuristic and gradient methods in civil works (Stoiber & Kromoser, 2021). The ultimate goal of optimization is to remove redundant structural components to achieve low cost, high quality and low pollution.

Table 4.2 shows the representative optimization strategies in some stages of the civil works. A variety of mathematical model methods are used to optimize the materials. The premise of innovation is to clarify the construction process model and life cycle research framework. Make a deep analysis of the structural components according to the proposed optimization strategy to obtain the new finite element model and the optimization scheme after multiple iterations. And calculate and analyze LCC, LCA, and SIA according to the systems design parameters to obtain the final SD data (Figure 4.3).

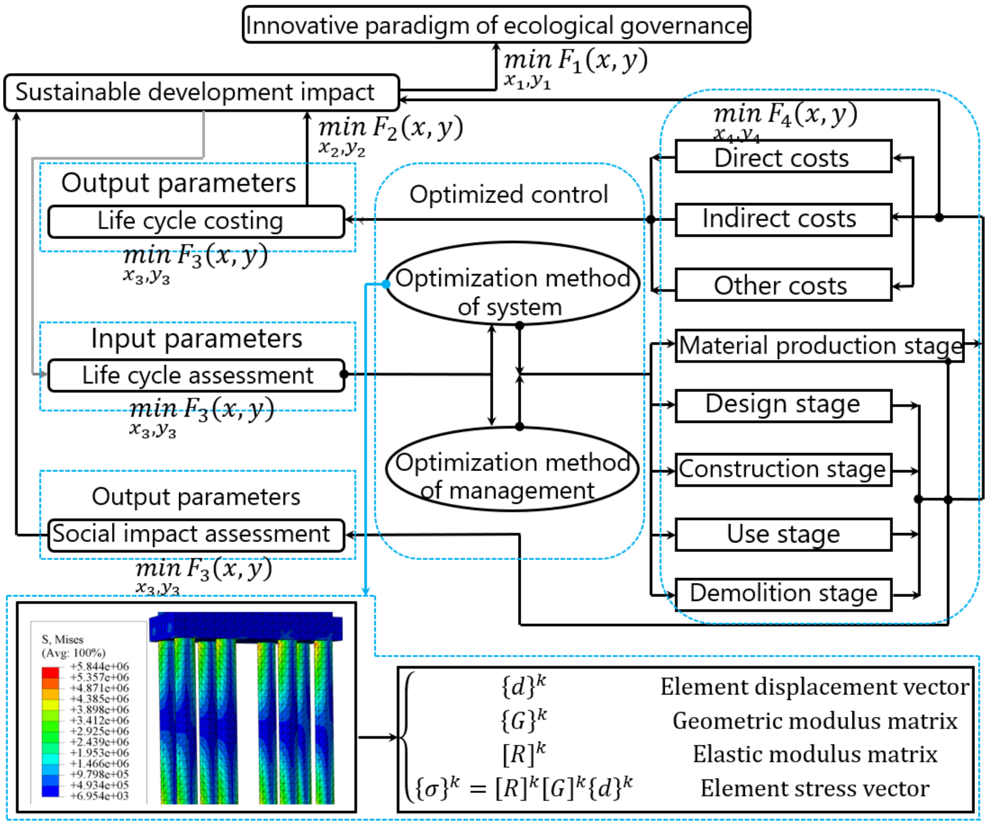


Figure 4.3. Structural optimization innovative description.

Sources: Own elaboration, based on part of data from WoS.

4.2. Mathematical optimization model of bridge

The TO of the bridge refers to the process of determining the shape, connectivity, and location of structural voids in the design domain. It provides architectural engineers with higher degrees of freedom based on limiting the size and shape of the structure and can deal with variables such as the component thickness, cross-sectional area and geometric characteristics of structural configuration, etc. Its scope of application also extends from the initial

Table 4.3. Classical TO mathematical theoretical model

Methods model of TO		
Methods	**Characteristics**	**Mathematical model**
Density-based methods	The objective function is minimized by operating on a fixed domain of finite elements, identifying whether each element should consist of solid material or voids.	$\min: f(\rho, U)$ Subject to: $K(\rho)U = F(\rho)$ $g_i(\rho, U) \leq 0$ $0 \leq \rho \leq 1$ (Bendsøe & Sigmund, 1999)
Hard-kill methods	The simplicity with which it can be used with commercial finite element software packages enables designs with clearly defined structural boundaries without intermediate or grey materials.	$\min: c = U^T K U$ *Subject to:* $\frac{V}{V_0} \leq V_f$ $KU = F$ $x = [0,1]$ (Huang & Xie, 2010)
Boundary variation methods	It can a state-of-the-art method for structural and multidisciplinaryTO. The theory stems from the structural boundary implicit function of shape optimization techniques.	$\min: C(u, \emptyset)$ $= \int_{\Omega} E\varepsilon(u)\varepsilon(u)H(\emptyset)d\Omega$ subject to: $\int_{\Omega} H(\emptyset)d\Omega \leq V_f$ $\int_{\Omega} E\varepsilon(u)\varepsilon(v)H(\emptyset)d\Omega = 0 \forall v \in U$ (Kobayashi, 2010)
Bio-inspired cellular division-based method	Utilize discrete and continuum-like structural principles to develop program-controlled topology layouts, as well as topology development in stages.	$A \rightarrow B[+A]x[-A]B$ $B \rightarrow A$ $x \rightarrow x$ (Deaton et al., 2014)

Sources: Own elaboration, based on part of data from WoS.

linear response to material design, heat transfer, structure, fluid flow, aeroelasticity, acoustics, and other multidisciplinary combinations (Eschenauer & Olhoff, 2001).

Table 4.3 shows a relatively mature and classic application model from 1990 to 2015. It focuses on the development and improvement of finite element TO. It reminds researchers that randomness also affects the optimization process under the interference of discreteness and uncertain factors. Therefore, how to improve the randomness of data under the agreement of load and boundary conditions is also the key to improving the application of robust optimization design. In the framework of the theoretical model of this thesis, this interference problem will be solved, and the problem of resistance to discrete data will be improved through sensitivity testing and finite element compensation.

4.2.1. Analysis of relevant evaluation indicators

The bridge structure depends on multi-material TO. The discreteness and optimization problems of material and topology variables should be solved in the analysis process. Good optimization combination includes material (phase) mixed interpolation, multi-purpose function application and homogeneous material with compensated interpolation, etc. The parameters considered include size variables, frame structure form, and material properties (stiffness, density, strength response, and stress concentration).

4.2.1.1. Multi-material TO

Under the combined load, all bridge components are stressed and deformed due to the material characteristics. The best size distribution and structural shape can be obtained with the displacement and deformation of isotropic, homogeneous, and linear elastic materials. Elastic modulus, yield stress, and compensation ability are usually used to analyze the robustness of the optimized structure.

Figure 4.4-a is the structural comparison of the local TO of the CSB before and after the optimization. The Pier column, pier head, main girder, and asphalt concrete bridge deck have different degrees of deformation (Figure 4.4-b). The bending stiffness and dynamic stiffness of the structure finally tend to be stable with theloading frequency of the structural load. The following evaluation indicators can be determined according to the binding effect (Kobayashi, 2010):

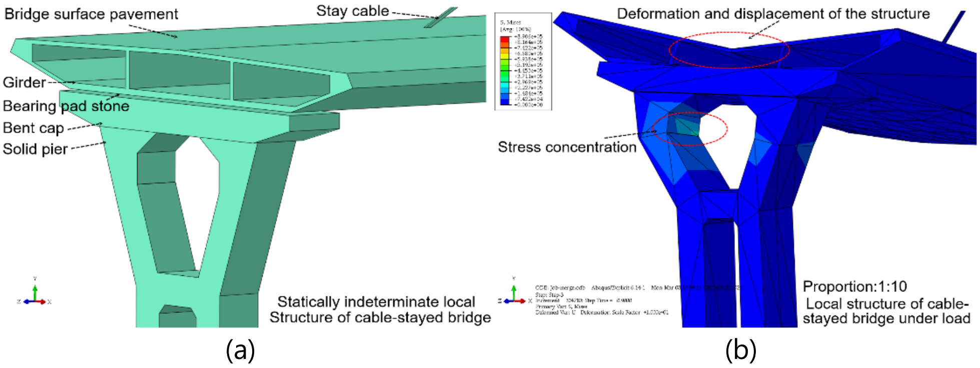


Figure 4.4. Comparison of CSB TO (partial). (a) Bridge structural parts marking. (b) the bridge structure is twisted and deformed.

Sources: Own elaboration, based on part of data from Abaqus software.

Eq.4.8

$$\min_{SI} S_T = \sum_{\Upsilon=1}^{n} l_\Upsilon \rho_\Upsilon A_\Upsilon$$

$$\begin{cases} \rho_\Upsilon \in (0,1) \\ \overline{K}_c < K_c, \overline{K}_c \subset (0, K_{\max}) \\ \overline{K}_d < K_d, \overline{K}_d \subset (0, K_{\max}) \\ E_e = E_e(\rho_\Upsilon) \in (E_1, E_2, \cdots, E_n) \end{cases}$$

SI is the statically indeterminate structure; S_T is the total mass of the framework structure of the bridge; n is the number of components; l_Υ is the longitudinal homogenization length of the bridge (m); ρ_Υ is the homogenization density of the bridge; A_Υ is the homogenized section area (m^2); $\overline{K}_c$ and $\overline{K}_d$ are the optimal torsional and bending stiffness; K_c and K_d are the mean torsional and bending stiffness; K_{max} is the maximum torsional, and bending stiffness in the maximum stress concentration area; E_e is the elastic modulus of various materials.

Eq. 4.8 is a multi-material TO evaluation indicator system. In the process of multiple iterations, the design variables of the bridge components will be balanced many times; the section characteristics, size parameters, area, moment of inertia and various constraints will be redistributed evenly; the dimensions of redundant structures will be constrained, to realize the final TO paradigm.

To achieve the best structure, architects need to verify the safety and quality of the system, set a composite parameter to limit and monitor the robustness of the design, and specify the parameter sensitivity (Huang & Xie, 2010).

$$\frac{\partial \bar{K}_C}{\partial \bar{\rho}_Y} = \frac{1}{\delta_n} \sum_{Y,C=1}^{c=\delta_n} \left| -\frac{F_{Y,C}}{(\delta_n)^2} \frac{\delta_n}{\partial \bar{\rho}_Y} \right|$$

δ_n is the average sensitivity after multiple iterations.

4.2.1.2. Multi-objective TO model

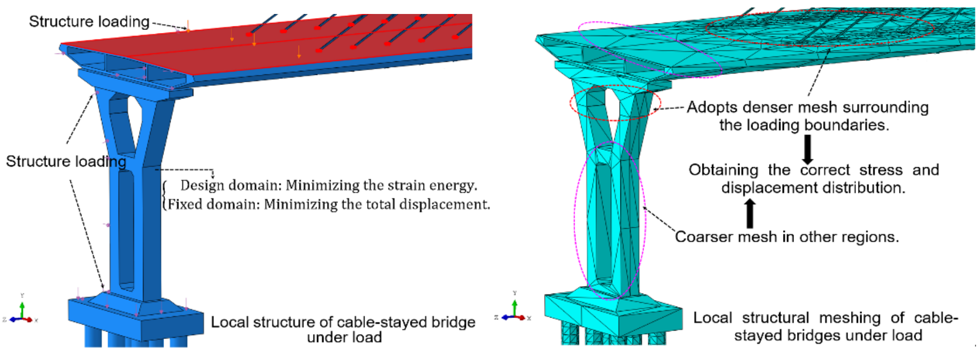
In 4.2.1.1, the multi-material TO characteristic parameters are studied. In project practice, engineers should consider the structure's mass, weight, displacement, stiffness, frequency, bridge load, ambient temperature, and comprehensive stress of sudden and unpredictable loads. To solve these problems and avoid parasitic effects in the action area, some researchers have proposed to adopt a non-monotonic approximate model (Bruyneel & Duysinx, 2005) and homogenization design (Rouhi & Rais-Rohani, 2008). Improved non-uniform interpolation function modeling and other methods (Félix et al., 2020).

Through the literature analysis, it can be found that the discrete continuum structure only considers the design domain and realizes the minimum strain energy. In structural mechanics, the structural stiffness should be maximized, and the total displacement and deformation should be minimized when the total strain energy is minimized to achieve the fixed domain's optimization objective.

Eq.4.9

$$\begin{cases} \text{Find: } \rho_e (e = 1,2,\cdots,ň); \text{Min: } f_{obj} \\ \text{Subject to: } 0 < \sum_{i=1}^{n} V_e \rho_e \le f_0 V_\Omega \\ \quad 0 < \rho_{\min} \le \rho_e \le 1 \end{cases}$$

ň is the number of finite elements (design domain Ω); V_Ω is the volume of the design domain; f_o is the allowed volume of structural materials; V_e is the finite element volume; ρ_{min} is the lower limit of design variable; f_{obj} is the overall objective function of the structure (S. Zhang et al., 2021).



(a) (b)

Figure 4.5. Volume domain and fixed domain during TO of CSB (partial).(a) bridge structural

constraints and mechanical loading distribution. (b) modular distribution of bridge structural stress.

Sources: Own elaboration, based on part of data from Abaqus software.

Compared with Eqs. 4.8 and 4.9, the difference is that in the process of TO, as the volume domain cannot meet the discrete optimization requirements of some structures, it is necessary to use more dense grids to constrain the loading boundary, increase the number of elements in irregular grids, better perform the analysis and obtain the number of parts required by TO, more accurate stress and displacement distribution, so as to minimize the strain energy and the total displacement. According to Figure 4.5-a, the three-dimensional structure TO is more suitable for Eq.4.9 through the analysis of structural mechanics, optimization, and partial differential Eq modularization process.

It has the same effect as the sensitivity. In order to control the minimum structure size and filter design variables, the relative density is added to solve this problem.

It has the same effect as the sensitivity. In order to control the minimum structure size and filter design variables, the relative density is added to solve this problem (S. Zhang et al., 2021).

Eq.4.10 Structural design of relative density method

$$\bar{\rho}_e = R_{\min}^2 \nabla^2 \bar{\rho}_e + \rho_e$$

R_{min} is the size of the filtering; $\bar{\rho}_e$ is the filtered design variable; ρ_e is the original variable.

According to Eqs. 4.8 and 4.9; Figure 4.5-b, the critical influence parameters are given to realize the structural objective function model under the design variables and constraints. The lightest and hardest structural design is ensured by optimizing the reasonable distribution of materials.

4.2.2. Establish finite element model of bridge

Through the research process in 4.2.1, a TO mathematical model is established in this thesis, and the research case is the super large CSB with a single tower and T-beam. The loads in the design stage mainly include permanent load, traffic, and dynamic load, permanent, variable, accidental, and seismic forces. In view of the complexity and uncertainty of the research, the following principles are agreed upon:

a) For structure TO at the bridge design stage, only static and partial dynamic mechanical properties of statically indeterminate structures under environmental loads are studied.

b) The loads generated in TO are studied according to permanent load (bridge structure gravity, additional gravity) and variable load (vehicle load, vehicle impact force, wind load, and temperature influence), excluding seismic load.

c) During the process of TO, the main structure, especially the foundation structure components (pile foundation) shall not be damaged.

d) The limited control index shall be strictly measured, and one index exceeding the standard indicates the failure of structural optimization.

e) The research and analysis are carried out according to the case's real state and actual construction state, which cannot be idealized and divorced from the natural state.

f) It is strictly prohibited to use plate and shell units to replace the solid structure, which will result in the distortion of research data and the approximation of conclusions, laying a solid foundation for the accurate analysis of the internal microstructure of the structure.

Eq.4.11 theoretical framework of TO

According to the requirements of structural static stress, under the action of external load, TO is (ZhiWu Zhou et al., 2022):

$$\gamma_{i1},\gamma_{i2},\cdots,\gamma_{im}\ ,\ \gamma_{l1},\gamma_{l2},\cdots,\gamma_{ln}\ ,\ \sum_{i=1,\cdots,m}^{l=1,\cdots,n}\left(\gamma_{im,\cdots,km}^{ln,\cdots,kn}\right)\ ,\quad \min\ S=\sum_{\alpha=1}^{\alpha=m}\omega_{i\alpha}\gamma_{i\alpha}+\sum_{\beta=1}^{\beta=n}\omega_{l\beta}\gamma_{l\beta}+,\cdots,+\sum_{i,\cdots,k}^{l,\cdots,k}\omega_{k(i,\cdots,k)(\alpha,\cdots,\beta)}\gamma_{k(l,\cdots,k)(\alpha,\cdots,\beta)}$$

Meanwhile, $\max\left[\max\left(\sigma_{i\alpha,\cdots,l\beta,\cdots,k(\alpha,\cdots,\beta)}^{V}\right)^{k}\right]\leq\max_{n,\cdots,m}\left(\alpha^{i}\cap\alpha^{l},\cdots,\cap\alpha^{n,\cdots,m}\right)$

γ_{im} and γ_{ln} are the unit grid gravity under different loads (KN); S is the total gravity of structure (KN); $\left(\sigma_{i\alpha,\cdots,l\,\beta,\cdots,k(\alpha,\cdots,\beta)}^{V}\right)^{k}$ is the Von Mises stress generated by the structure under the action of k groups of loads ($\mathrm{Kp_a}$); $\alpha^{i}\cap\alpha^{l},\cdots,\cap\alpha^{n,\cdots,m}$ is the maximum Von Mises stress controlled by the structure under k groups of loads ($\mathrm{Kp_a}$).

$$\begin{cases}\gamma_{i\alpha}\in\{0,1\},\alpha=1,2,\cdots,m & \text{The } i-t\text{ructural element after } \alpha \text{ iteration}\\ \gamma_{l\beta}\in\{0,1\},\beta=1,2,\cdots,n & \text{The } l-\text{structural element after } \beta \text{ iteration}\\ \gamma_{k(l,\cdots,k)(\alpha,\cdots,\beta)}\in\{0,1\},\ \alpha,\cdots,\beta=l,\cdots,k & \text{Effective iteration under other loads}\end{cases}$$

The effective element retained under load is recorded as x_z,

$$\text{then}\begin{cases} x_1 \subset \{1,2,\cdots,m\} \\ x_2 \subset \{1,2,\cdots,n\} \\ \vdots \\ x_z \subset \{1,2,\cdots,k\} \end{cases}$$

Sensitivity vector: for the displacement vector $\{d\}^k$ of each element in the three-dimensional space, the stress vector of the k th element is $\{\sigma\}^k$ = $\{\sigma_{xx}, \sigma_{yy}, \sigma_{zz}\}_k^l$, which can be expressed as $\{\sigma\}^k$ = $[R]^k[G]^k[d]^k$, where $[R]^k$ is the elastic modulus matrix; $[G]^k$ is the geometric modulus matrix; $[d]^k$ is the product of displacement matrix; $[D]^k$ is the energy matrix; ($[E]^k$) and $\frac{\sigma w_n}{\sigma s_n}$ (Eq.4.6 sensitivity) are the product.

Eq.4.12 Formula of sensitivity changes

The sensitivity changes of displacement vector in the optimization process are

$$\{\triangle\,\sigma\}_k^v = \begin{bmatrix} \triangle\,\sigma_x \\ \triangle\,\sigma_y \\ \triangle\,\sigma_z \end{bmatrix}_k^v$$

$$= [R]^k[G]^k\{\triangle\,d\}^k, \text{ then} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_z \end{bmatrix}\{\sigma\}^k = \begin{bmatrix} \sum_j x_{1j}{(u^{ij})}^T \\ \sum_j x_{2j}{(u^{ij})}^T \\ \vdots \\ \sum_j x_{zj}{(u^{ij})}^T \end{bmatrix}[K^i]\{d^i\}$$

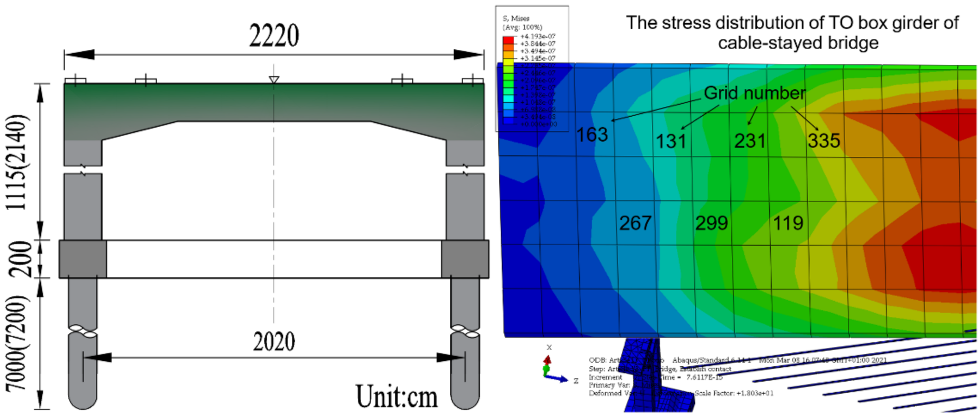
$x_1,\cdots,x_z$ is the number of rows of matrix$[R]^k[G]^k$; $\{\sigma\}^k$ is the displacement sensitivity vector of k elements; $x_{1j}{(u^{ij})}^T$ $(j = 1,2,\cdots,n)$ is the displacement of i elements caused by the j th element. According to $x_{zj}(Z = 1,2,3,\cdots,n; j = 1,2,3\cdots,n)$;$\left(u^{ij}\right)^T$ $(j = 1,2,3,\cdots,n)$, the balance Eq of load can be obtained. The stress variation of the k^{th} element is $\begin{bmatrix} \triangle\,\sigma_x \\ \triangle\,\sigma_y \\ \triangle\,\sigma_z \end{bmatrix}_k^v = \begin{bmatrix} \tilde{u}_{ik}^1 \\ \tilde{u}_{ik}^2 \\ \tilde{u}_{ik}^3 \end{bmatrix}[k^i]\{d^i\}$, so the Von Mises stress of the k^{th} element is $\tilde{\sigma}_k^{vm} = \sqrt{\sigma^{1}{}_x^2 + \sigma^1{}_y^2 - \sigma^x\sigma^y + 3\Upsilon^1{}_{xy}^2}$, and the sensitivity vector of the k^{th} element is $\triangle\,\sigma_k^{vm}$ = $\tilde{\sigma}_k^{vm}$-σ_k^{vm}.

In the analysis process of structural TO, the mises stress analysis is carried out for structural bridge components. According to the analysis results, whether it is a practical or invalid component is judged. The purpose of finite element TO for practical details is to remove weak branches and reduce material consumption. The qualification of the optimized component can be judged according to the sensitivity vector.

4.2.3. 3D visualization innovation of bridge model

TO study is suitable for the macro and microstructure of periodic structure multiphase materials. Composites are composed of three-phase or more phase materials. It is minimal to use one-phase and two-phase targets in the research, especially it is difficult to find the microstructure changes inside the structure. The two-dimensional system can display the detailed changes of some parameters but lack the sense of space and micro three-dimensional (Figures 4.6-a, d). However, 3D structure solves these problems.

Figure 4.6-b is the top surface of TO rear box girder. Seven groups of elements are selected as the research monomer, and the distance from the stress concentration point increases in turn. The stress distribution area and the increase & decrease direction can be seen in the stress distribution diagram. Figure 4.6-c shows a monomer removed from 7 groups of elements, and the dispersion and flow direction of stress in the microstructure of each group of features can be seen. Each effective stress interface is clear and unique. Figure 4.6-d shows the change of pressure with time. Each group of elements has a consistent stress trend, and there are three major stress mutations in the process of structural TO. Finally, it tends to be stable. Figures 4.6-e and f are the displacement curve with time. There is an excellent displacement change in the TO process of seven elements, and the final displacement of each group of elements is more than 2.03m. Node 131 reaches 2.53m, indicating that the structure has been damaged.



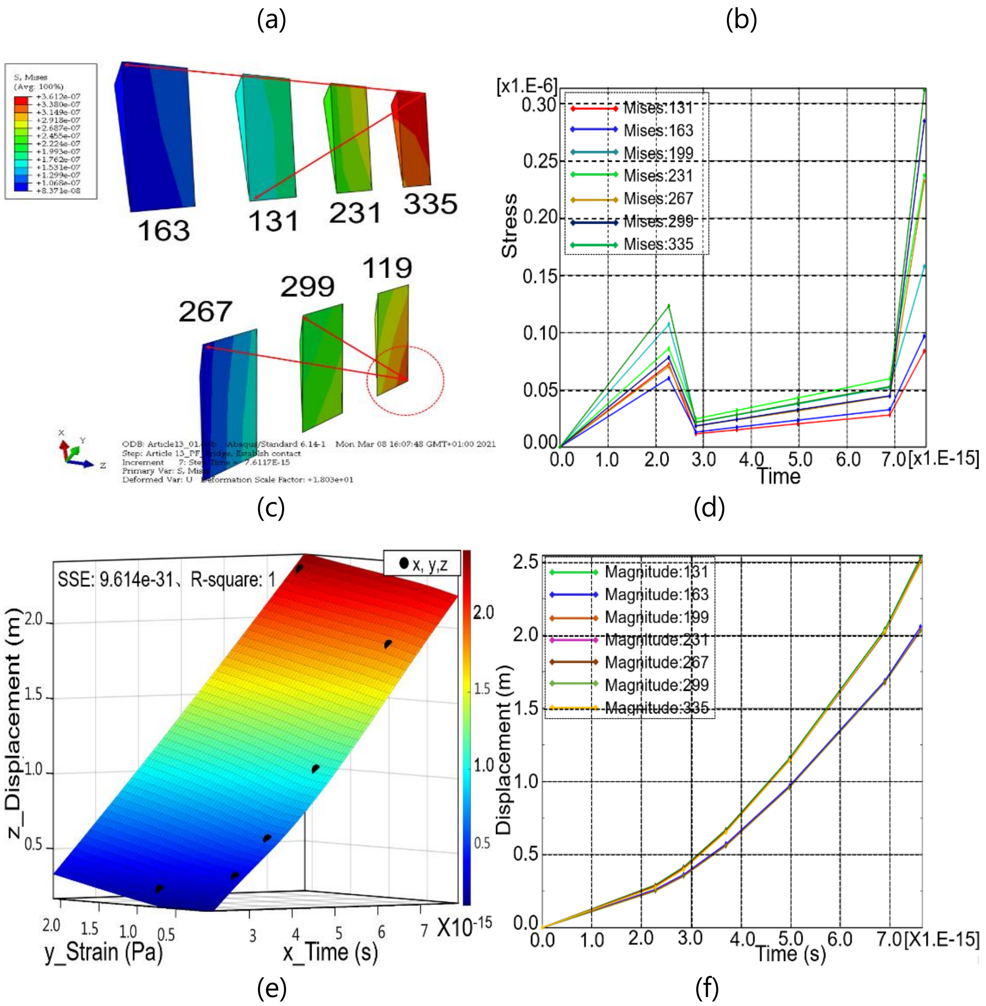


Figure 4.6. Microstructure of box girder after TO of CSB (partial). (a) two-dimensional structure. (b) three-dimensional structure. (c) analysis of elements. (d) stress of every elements. (e) seven-elements thin-plate spline interpolation fitting. (f) displacement of every elements.

Sources: Own elaboration, based on part of data from Abaqus, Matlab software.

4.3. Determine project management optimization evaluation indicators through selected literature analysis

Due to the complex process, multi-level supply chain, and many interference factors, an infrastructure project is a complex management project involving strict time agreements and distributed logistics plans. A new project management model is proposed to aim at how to efficiently realize strategic interests and objectives of assignments, practical implementation, maximum benefits, sustainable management, and integration of resources in a controlled environment. Initial project management is defined as a project portfolio model that calls on the same resources to achieve the set objectives and benefits of the project and focus on the impact and development of the next stage (Shehu & Akintoye, 2009).

The research results show that project management is a comprehensive, structured, and discrete framework that needs to coordinate, allocate and adjust resources, as well as plan and implement the best scheme through management.

The project management integration model proposed in *ISO21500* includes five process management cycles: start, plan, implementation, control, and end. The fields involved have quality, scope, time, cost, resources, risk, communication, procurement, and integration (Takagi & Varajão, 2022).

As the success criteria and factors, performance and evaluation indicators of project management are interactive and evaluated in dynamic control, the critical integration methods in the process of the project management model are analyzed, and the evaluation indicators are monitored and selected (Table 4.4).

According to Table 4.4, the content and the research case of this thesis are determined. The project management model's critical optimization parameter framework system is determined as the paradigm standard of case analysis and management optimization. The key influencing factors of project management are divided into seven levels. The assessment indicators of each level comprehensively judge the difference in optimization quality, and then the robustness is assessed. At the same time, the measurement indicators feedback that high-end project management focuses on safety, quality, and economic cost control and pays more attention to the environment, community, and ecological protection (Figure 4.7).

Readers can find in the seven impact indicators that the interval of each layer is expanding the multi-constraint compensation effect. The social impact indicators and sustainable development evaluation indicators are gradually improving, which also shows that this thesis's research direction and field are gradually tending towards sustainability, which fully conforms to the research theme. Therefore, in the optimization design, the boundary conditions mainly analyze the sensitive influence of materials, environment, management, and human external factors and scientific compensation. Improve the constraints, reduce the interference factors, and set up the sensitivity measurement standard for the school team and measure its effectiveness.

Table 4.4. A survey of important parameters and models of classic project management

The framework proposed	Project management performance and indicator	Mathematical model
Project integration management (Demirkesen & Ozorhon, 2017a)	The project scope, time, communications, risk, cost, integration, quality, human resource, procurement, safety, environmental, stakeholder, financial, and claim management.	An online questionnaire was designed
Agile project management (Arefazar et al., 2019)	Full delegation of authority to the project team members,Monitoring and evaluating the progress of the project constantly, Participation of the client and end users at all stages of the project, Continuous improvement, Facilitating communication between project areas and project team members, Identifying and analysing the actual stakeholders, Time management, Early return of investment, flexible work flow, Obtaining the requirements throughout the project's lifecycle.	The form of questionnaire
Whole life project management (N. Wang et al., 2014)	The whole life of the building and infrastructure projects from initiation, tendering, design, construction and operation. Environmental Management, Community Engagement, Health and Safety, Whole Life Costing, Waste Management, Energy Efficiency.	Though a case study
Lean Management (Wu et al., 2019)	Work speed, Transparency, Reduce waste, Reduce cost, Client communication, Traffic management, Risk management, Deliverable understanding.	Linear regression model
Construction management process reengineering (Cheng & Tsai, 2003)	Business management, Human resource management, Financial management, Construction bidding contracts, Cost estimates construction planning, Purchase sub-contracting, Construction management, Post sales service.	Management information technology system
Materials Management in the Construction Industry	Materials requirements planning, project acquisition strategies, purchasing and subcontracting, expediting, supplier quality management, transportation and logistics, site	Secondary surveys and case studies

(Caldas et al., 2015)	materials management, and materials planning for operations and maintenance turnover.	
Project management body of knowledge (Demirkesen & Ozorhon, 2017b)	Project integration management, project scope management, project time management, project cost management, project quality management (14).	Online questionnaire
Structural Eq Modeling for Safety Management (Sunindijo & Zou, 2013)	Visualizing, decision making and prioritizing, diagnosing problems, systemic problem solving, planning, organizing, and goal orientation.	Mixed methods research design

Sources: Own elaboration, based on part of data from WoS.

The above analysis methods and ideas have proved effective and robust in subsequent case data analysis.

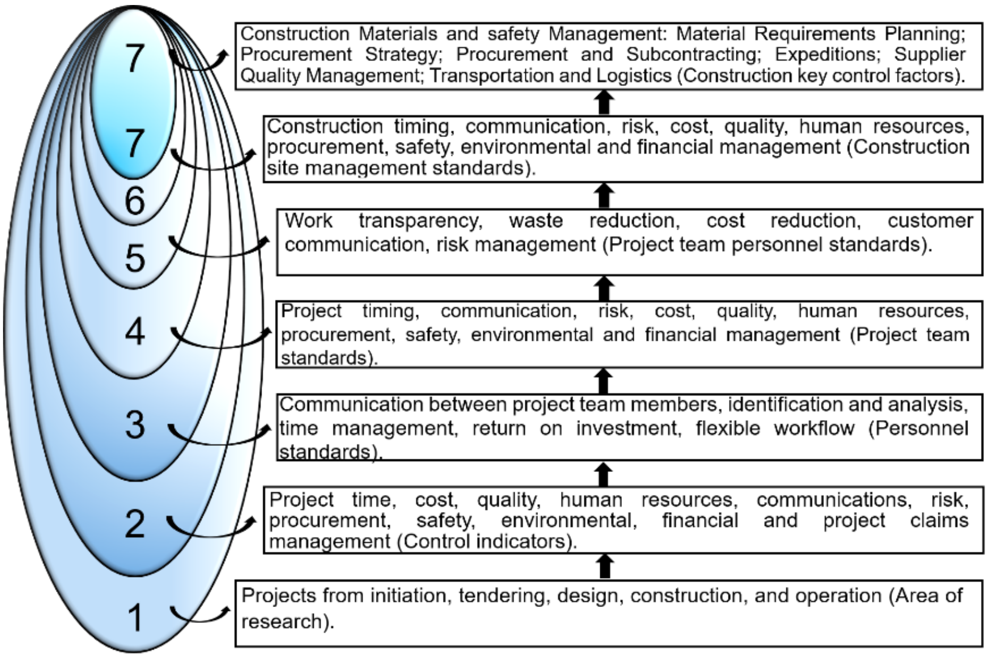


Figure 4.7. Project management optimization key control indicators.

Sources: Own elaboration, based on part of data from WoS.

4.3.1. Current status of project management model

The models commonly used in project management include fuzzy technology, genetic algorithm, case-based reasoning, meta-synthesis model, artificial neural network, and various combination frameworks (Koke & Moehler, 2019). The initial view of project management is that: the project team is faced with sudden career management and multi-standard and high-level intensive system objectives and tasks; plays a critical guiding role in the SD of the organization and society through project management; and has the responsibility to improve the community comprehensively.

To better understand the current situation of project management. The Scopus literature search tool was selected, and 24,256 kinds of literature were obtained with the keywords: project management, article, engineering, environmental science and social sciences, showing that there is a high research literature on project management. A total of 6,976 kinds of literature in 2018, 2019, 2020, and 2021 were selected, and Citespace was used for the cluster analysis.

The analyses are concluded as follows: In the four-year keyword clustering network map, the most commonly used ones are swat model, physical activity, community participation, building information, business model, mathematical model, construction project, carbon emission, machine learning, everglades ecosystem, and loess plateau. See Table 4.5 for the keywords extracted in each clustering region.

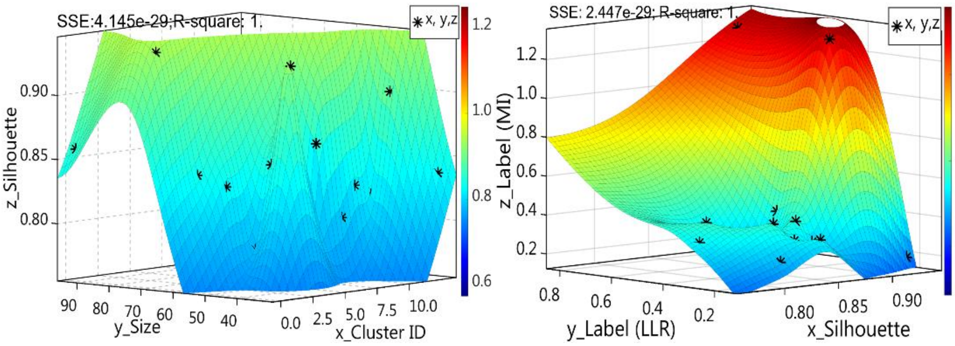


Figure 4.8. Research model clustering contour value and extraction algorithm fitting analysis.

Sources: Own elaboration, based on part of data from Matlab software analysis.

Table 4.5. Keyword clustering network graph analysis conclusion

Cluster ID	Mean (Year)	Label (LSI)
0	2018	Case study; soil erosion; water resource; loess plateau; water resources management | water quality; water allocation; water availability; irrigation water; a case study.
1	2018	Case study; pilot study; physical activity; controlled trial; medical student | construction project; risk assessment; critical success factor; moderating role; risk factor.
2	2018	Case study; construction project; public-private partnership project; river basin; construction industry | case studies; SD; community participation; urban context; smart city development.
3	2018	Case study; building information; building information modeling; integrated project delivery; project performance | construction project; construction industry; critical success factor; construction site; sustainable building.
4	2019	Case study; construction project; business model; SD; energy saving | risk assessment; construction industry; critical success factor; developing countries; interpretive structural modeling.
5	2018	Case study; construction project; risk assessment; public-private partnership project; public-private partnership | mathematical model; pavement maintenance; resource leveling; water management; mega construction project.
6	2018	Construction project; construction industry; critical success factor; case study; project performance | public-private partnership; risk management; ppp project; risk analysis; private partnership.
7	2018	Case study; carbon emission; circular economy; environmental performance; economic assessment | Construction project; construction industry; governing knowledge transfer; deforestation monitoring; digital twin.
8	2018	Case study; risk assessment; artificial neural network; novel approach; learning method | machine learning; construction project; learning technique; using machine; learning approach.
9	2018	Case study; conceptual framework; marine ecosystem; ecosystem service; everglades ecosystem | loess plateau; soil erosion; land use change; northern China; land use.
10	2018	Loess plateau; ecosystem service; land use change; soil erosion; north China plain | case study; land use; spatial distribution; south Asia; groundwater recharge.

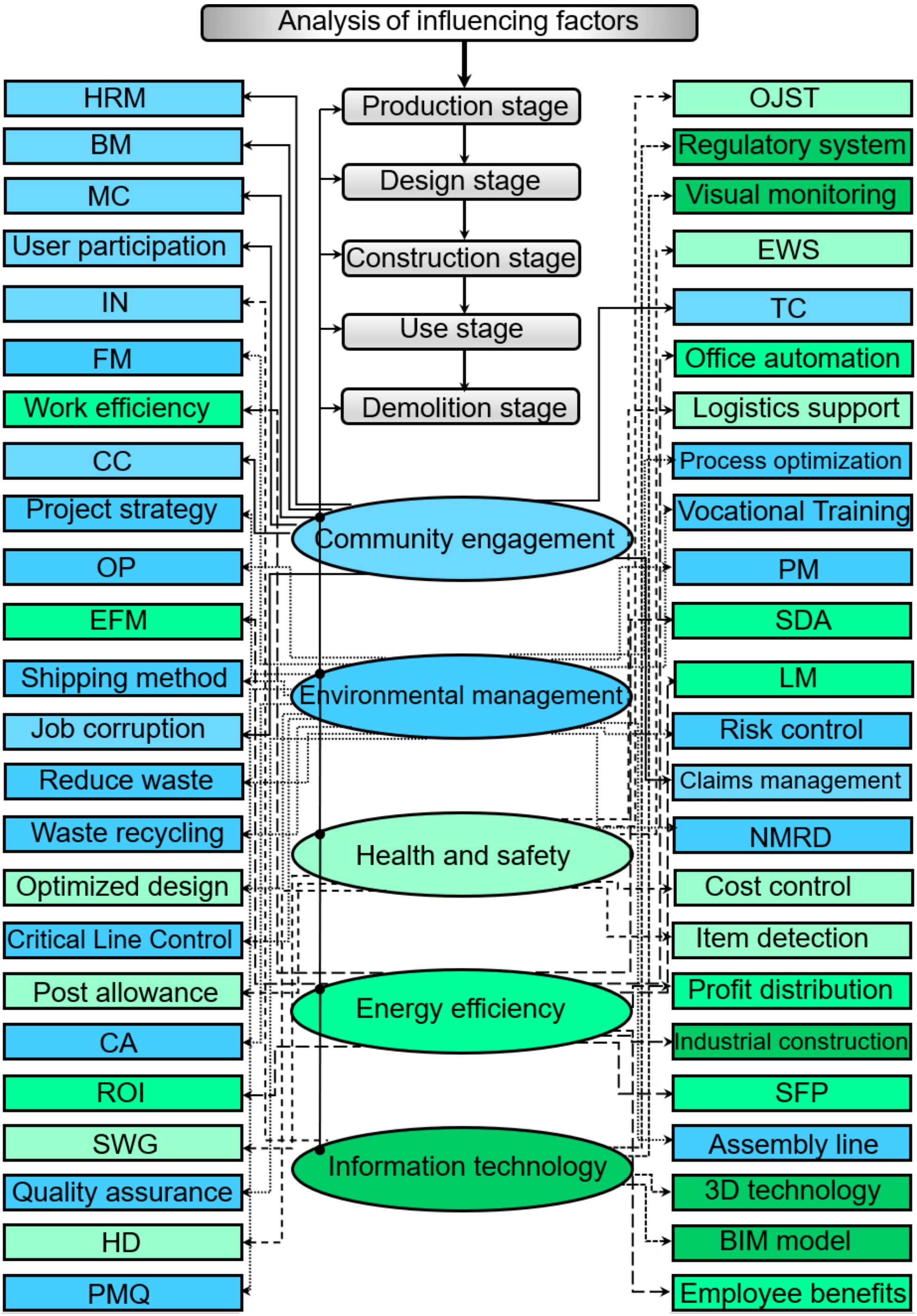
Sources: Own elaboration, based on part of data from WoS.

According to Figure 4.8, the mathematical model – thin-plate spline interp-

-olant fitting analysis is adopted for the clustering of the research model, and the critical model (SSE=0) presents discrete distribution. The fitting conclusions are consistent with the data shown in Table 4.5. The data of the research model are concentrated in the bottom area, and there is a small amount of data distributed at the top.

4.3.2. Analysis of influencing factors

The project management can be interfered with by multiple objectives such as quality, construction period, cost, and risk, which are not independent. Give the difference between each project type and natural environment, the realization of project objectives will be restricted and affected by: the machine category, material selection, hydrological conditions, meteorological changes, topography and geology, construction technology, and management measures and operating environment. Syed Hassan Raza (2021) divided the influencing factors into internal and external sources. The internal sources include organization, systems/procedures, engineering, quality assurance/control, sponsors, finance/business, human resources, and project management, based on the interview and evaluation of experienced project managers and teams. The external sources include general security, contract/law, competitors, customers, and logistics, which focus on the restrictions of the natural environment and social factors. Tatjana (2016) put forward the control measures and effective means of production, technology, economy, politics, organization, ecology, and risk factors through the investigation of documents and publications and analysis of the internal and external impact of the project environmental management system from multiple dimensions.It can promote the realization of organizational management and economic competitiveness objectives, and the consistent and effective management of processes and resources. Jiwei (2021) divided the EPC project management mechanisms and factors into vertical collaboration and horizontal collaboration and proposed to control the overall collaborative operation of progress, quality, cost and information security, organization, process, business, resources, and institutions through informatization, rational resource allocation, and system guidance. Michael (2018) assessed the influencing factors of the building design management, and listed ten issues based on an interview survey, including cultural differences, insufficient project documents, handover between different project teams, constructability and maintainability, the willingness of participants to cooperate.


Analysis of influencing factors
Production stage
Design stage
Construction stage
Use stage
Demolition stage
HRM
BM
MC
User participation
IN
FM
Work efficiency
CC
Project strategy
OP
EFM
Shipping method
Job corruption
Reduce waste
Waste recycling
Optimized design
Critical Line Control
Post allowance
CA
ROI
SWG
Quality assurance
HD
PMQ
Community engagement
Environmental management
Health and safety
Energy efficiency
Information technology
OJST
Regulatory system
Visual monitoring
EWS
TC
Office automation
Logistics support
Process optimization
Vocational Training
PM
SDA
LM
Risk control
Claims management
NMRD
Cost control
Item detection
Profit distribution
Industrial construction
SFP
Assembly line
3D technology
BIM model
Employee benefits

Notes: HRM = Human resource management; BM = Business management; MC = Mechanized construction; IN = Information network; FM = Financial Management; CC = Customer communication; OP = Organization planning; EFM = Environmentally friendly materials; CA = Construction automation; ROI = Return on investment; SWG = Safe work guarantee; HD = Hazard determination; PMQ = Project Manager Qualification; OJST = On-the-job safety training; EWS = Early warning system; TC = Team communication; PM = Purchasing management; SDA = Supply and demand allocation; LM = Logistics management; NMRD = New material research and development; SFP = Semi-finished products (abbreviations apply to Figure 4.9.).

Figure 4.9. Influence factor analysis index of project management optimization.

Sources: Own elaboration.

in future projects, design change, the effectiveness of communication channels and methods, rework required to correct errors, level of litigation and claims, and user satisfaction with project products.

Concluding that the design management can promote the improvement of comprehensive strength in this field through government regulations, quality improvement, and integration and utilization of the design platform.

In this thesis, four different fields and literature directions are selected to investigate the evaluation factors. The author finds that the project management model is a highly complex system restricted by uncertain factors. And the decision-making and management are determined by multi-factor and multilevel direct and indirect factors of the project, which is different from the fixed management model and management idea of the manufacturing and service industry.Therefore, it has discreteness and diverse characteristics in determining the paradigm. However, its life cycle is fixed, including preparation, design, construction, service, and demolition. According to the literature survey, 48 influencing factors are determined as quantitative variables for effective decision-making of project management optimization in this thesis (Figure 4.9).

4.3.3. Establish project management optimization model

Project management is a favorable guarantee for ensuring project completion and obtaining a high return on investment. Still, it involves the planning and implementation of numerous tasks, which may lead to a lot of complex information and work tasks and decision-making and management defects of collapse and delay. Therefore, the critical path decision model is significant for the progress and completion of large-scale projects. Aiming at determining the critical path, Hazem Abdallah proposed three parameters: the earliest event time, the latest event time, and slack time. However, the determination of the above parameters has the randomness of a probability density function, which is challenging to be accurately described in the definition stage (Abdallah et al., 2009). Determining the project management model on the critical path can obtain an optimal management scheme and eliminate the random uncertainty of interference factors and fuzzy data.

Necessary conditions for determining the optimal management model (Figure 4.10.) of key routes are as follows: a) Determine the nodes and routes in the project management stage, and mark each node's key influencing factors and node time. b) Select the best influence path and determine the total float, free float, and the total time with the most extended duration on the critical route. c) Analyze the influencing factors on the best influence path, and determine the influence interval and path range. d) Establish the mathematical model of multi-objective optimization to determine the optimal solution set under given constraints. e) Optimize the system to obtain the best project management model data.

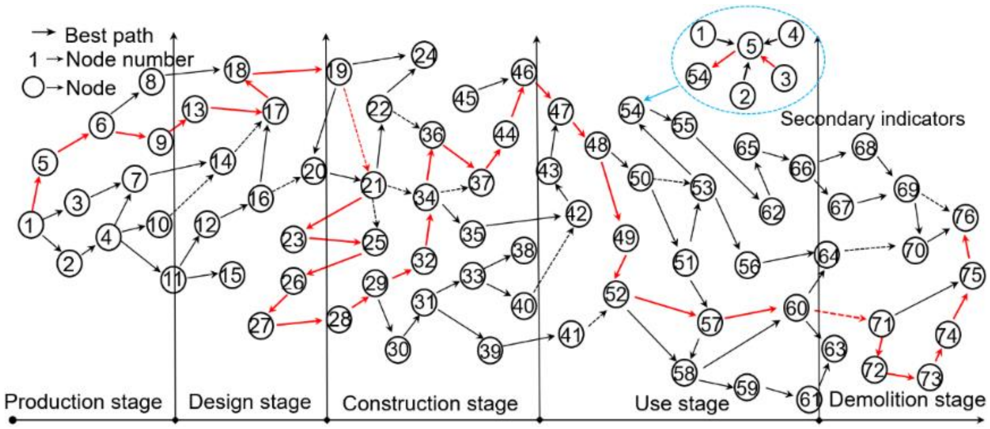


Figure 4.10. The best path node double-code network diagram.

Sources: Own elaboration.

Mathematical model of multi-objective optimization under minimization condition:

Eq.4.13 $$\text{Minimize} f(x) = [f_1(x_1), f_2(x_2), \cdots, f_h(x_{\check{n}})]^T$$

$$\text{Subject to}\begin{cases} g_i(x_{ń}) \geq 0 & i = 1,2,\cdots,k \\ h_i(x_{ń}) = 0 & i = 1,2,\cdots,l \\ x \in \Omega & x = [x_1, x_2, \cdots, x_{ń}]^T \end{cases}$$

$x_{ń}$ is the influencing factor variable; ƒ is h objective function vectors; g_i and h_i are equality constraints (Abdallah et al., 2009).

$$\begin{cases} x_1 = x_1'\overline{e_1} + x_2'\overline{e_2} +, \cdots, +x_m'\overline{e_m} \\ x_2 = x_1'\overline{e_1} + x_2'\overline{e_2} +, \cdots, +x_s'\overline{e_s} \\ \vdots \\ x_n = x_1'\overline{e_1} + x_2'\overline{e_2} +, \cdots, +x_p'\overline{e_p} \end{cases}$$

$x_1', \cdots, x_m'$ is the multi-level impact data of x_1; $\overline{e_1}$ is the weight factor of x_1'; $\overline{e_m}$ and $\overline{e_p}$ are the weight factors of x_m' and x_p'.

$$\text{Minimize} f(x) = \left[\sum_1^h f_n \left(\begin{cases} x_1 = x_1'\overline{e_1} + x_2'\overline{e_2} +, \cdots, +x_m'\overline{e_m} \\ x_2 = x_1'\overline{e_1} + x_2'\overline{e_2} +, \cdots, +x_s'\overline{e_s} \\ \vdots \\ x_{ń} = x_1'\overline{e_1} + x_2'\overline{e_2} +, \cdots, +x_p'\overline{e_p} \end{cases} \right) \right]^{\mathrm{T}} =$$

$$\left[\sum_1^h ƒ_n \left(\sum_m^p (x_{ń}\overline{e_p}) \right) \right]^T$$

The final mathematical model of project management is Eq.4.13. Further analysis is not conducted for the weight factor because the weight of each n-level of influencing aspect has an immediate impact on the analysis case, which is determined by the actual situation.

4.4. Management and domino effect at bridge engineering

Through the analysis of the critical project management parameters in Table 4.4 and the determination of the management parameters in Figure 4.7, it can be found that the project management optimization is affected by high-frequency factors, and the model also has a vulnerability and a series of linkage effects.

Aiming at how to characterize this phenomenon and measure the degree and frequency of influence, the domino mathematical model is established.

Domino's identification and evaluation of scenes are mainly based on the potential damage caused by the consequences of critical settings to other locations. Its two key elements are the upgrade probability of evaluation and the effects of losses and failures in other affected scenes (COZZANI et al., 2006). This research model framework aligns with the multi-factor, multi-level, and multi-interference characteristics of project management optimization.

4.4.1. Impact parameters of domino effect

The Domino model framework is mostly used for hazard analysis and qualitative assessment, and its key indicators are upgrade source and target. The model carries out a comparative evaluation with the upgrade threshold and determines the standard effect value of the assessment. If it is lower than this set value, it will not cause damage to the target project. Otherwise, it will trigger hazardous accidents. To further determine the data and frequency of multi-level influence in project management, domino is used to evaluate the impact of events.

Eq.4.14 The domino evaluation model is defined as follows

$$f_d^e = p_d f_p$$
$$f_s^e = f_d^e + f_p^e$$

f_d^e is the event frequency; p_d is the upgrade probability; f_p is the event triggering the upgrade; f_s^e is the frequency of overall secondary time; f_p^e is the frequency of secondary time. From Figure 4.9, it can be seen that the influencing factor is at above four levels. Usually, the first-level indicator will trigger multiple second-level indicators, and the second-level hand will activate multiple third-level indicators. In this case, assuming that each indicator combination represents a domino scenario, the probability of all influence indicators should be calculated. Therefore, the likelihood of the n-level hand is (Necci et al., 2015):

$$P_d^{k_m} = \prod_1^h \left[1 - P_d^i + \delta(i, J_m^k)\left(2 \times P_d^i - 1\right)\right]$$

P_d^i is the i-level secondary probability; J_m^k is a vector; k is the index of m group combination of secondary level; $\delta(i, J_m^k)$ is a function variable.

4.4.2. Domino effect innovation about bridge engineering

In Eq.4.14, the mathematical model of the domino probability indicator at each level is determined, but there is no determination method for the indicator value rule at each level. Therefore, the entropy weight method establishes the system judgment standard frequency at each level to solve this problem.

Eq.4.15 The entropy weight method index is determined

Firstly, the judgment matrix $B = \left(b_{ij}\right)_{n\times n}$ is established, and the frequency weight at each level is $a_j = \frac{v_j p_j}{\sum_{j=1}^{n}(v_j p_j)}$, $v_j = \frac{(1-s_j)}{\sum_{j=1}^{n}(1-s_j)}$, $s_j = -(ln\, n)^{-1}\sum_{i=1}^{n}\left(\frac{r_{ij}}{nr_{ij}}\right)$, $r_{ij} = \frac{b_{ij}}{\sum_{i=1}^{n} b_{ij}}$.

a_j is the weight of the j-level indicator; v_j is the information weight of the j-level indicator; s_j is the entropy value of the j-level indicator output.

Normalization processing:

For positive indicators: $c_{ik}^* = \frac{c_{ik} - \min\limits_{1\le i\le s}(c_{ik})}{\max\limits_{1\le i\le s}(c_{ik}) - \min\limits_{1\le i\le s}(c_{ik})}$

For negative indicators: $c_{ik}^* = \frac{\min\limits_{1\le i\le s}(c_{ik}) - c_{ik}}{\max\limits_{1\le i\le s}(c_{ik}) - \min\limits_{1\le i\le s}(c_{ik})}$

c_{ik} is the k-level frequency in the i-level evaluation unit; $\max\limits_{1\le i\le s}(c_{ik})$, $\min\limits_{1\le i\le s}(c_{ik})$ is the maximum and minimum k-level frequency in the evaluation unit.

Based on the indicator frequency determined in Eq.4.15 and the scope defined by entropy weight method, a comprehensive indicator evaluation model is established:

Eq.4.16

$$\text{Minimize } f(x) = \left[\sum_{1}^{h} f_n \left(\sum_{m}^{p}\left(x_n \overline{e_p}\right)\right)\right]^T \times \begin{cases} P_d^{k,m} \ge c_{ik}^* \\ c_{ik}^* \ge P_d^{k,m} \ge c_{ik}^* (\text{reverse}) \\ P_d^{k,m} \le c_{ik}^* (\text{reverse}) \end{cases}$$

Eq.4.16 is the final mathematical model after innovation: domino evaluation model based on entropy weight method.

4.5. Summary of this chapter

In the whole thesis, this chapter is not only the core part of TO but also the theoretical framework and system model of TO:

a) The LCC, LCA, and SIA research model is established based on the optimization framework to discuss their relationship and difference.

b) A multi-level planning impact model is established to solve the discreteness and uncertainty of data, and sensitivity evaluation parameters are set for each level to better display and measure the robustness of data.

c) TO structure mathematical model, multi-factor control, and multi-level strategy model are established in the theoretical model of optimization and innovation to improve the optimization efficiency and quality.

By analyzing the current commonly used multi-material and multi-indicator TO theoretical systems and models, the bridge TO mathematical model is established according to the characteristics of linear and nonlinear materials, which is also the final application theoretical model of the research case. It combines two paradigms and meets the academic requirements of design and fixed domains, laying a solid mathematical and research foundation for this thesis. Finally, the importance and superiority of 3D structure in the study are explained. It is a powerful scientific application tool that cannot be replaced by line surface structure and cannot show the microstructure.

In this chapter, the theoretical mathematical model of project management optimization is established, and the optimization influencing factors of this thesis are determined through the analysis of the influencing factors of the project management model in different stages and the published literature. Additionally, literature clustering network analysis is used to investigate and summarize the current situation of classical mathematical models (2018-2021). Based on the understanding of published literature, the influencing factors in the whole life cycle are divided and determined as the compensation element for establishing the project management model. Finally, given the uncertainty and discreteness of the influencing factors of bridge engineering, this chapter innovatively puts forward the domino evaluation model based on the entropy weight method. It establishes the mathematical theoretical paradigm of the innovation model. The interference of uncertain factors and the influence of emergencies in the multi-level management optimization are solved, laying a theoretical foundation for project management optimization.

Chapter 5. Results and discussion

This thesis selects the super large CSB with a complex structure as the research case, which has essential research value and makes up for the gap in this field (For detailed analysis, see Chapter 2).

The selection of research cases is essential for decision verification and high-quality data analysis, which is the strong evidence to verify the practicability and effectiveness of theoretical mathematical models (Dobrow et al., 2006). Readers can fully understand and systematically evaluate the theoretical model according to the objective case evidence.

For selecting research cases, it is necessary to formulate evaluation standards and logistic regression analysis of technical performance and determine the risk value of research cases through quantitative numerical standards. Therefore, a statistical evaluation model of the sensitivity of the variables is established to calibrate and evaluate (Swartz et al., 2008):

Eq.5.1 $$M_f^i = \sum_{i=1}^{i=\tilde{a}} [E_1 \times \lambda_1 \times (1 \pm \tau_s^1) +, \cdots, + E_{\tilde{a}} \times \lambda_{\tilde{o}} \times (1 \pm \tau_s^t)]$$

M_f^i is the case assessment standard conclusion; $E_1, \cdots, E_{\tilde{a}}$ are the assessment indicators (items); $\lambda_1, \cdots, \lambda_{\tilde{o}}$ are the evaluation coefficients of the indicators; $\tau_s^1, \cdots, \tau_s^t$ are affect the sensitivity coefficient (%).

The assessment index determines the path coverage target according to the questionnaire adjustment, test data, and similarity strategy. It is calculated by calculating the test similarity definition in each level's similarity path matrix constraint (Cartaxo et al., 2011). The sensitivity coefficient is the parameter data of the influence degree and sensitivity of the feedback assessment index on the assessment standard, which determines the importance of the assessment index.

Table 5.1. Study case control indicators and similar path assessments

Evaluation index	Impact factor	Score (00-50)					
		0	1	2	3	4	5
Study the overall fit of the model	Consistency of research direction					√	
	Mathematical model similarity						√
	The coherence of the analysis system					√	
	Innovativeness of the theory						√
	Originality					√	
	Academic contributions						√
	Clarity of research structure						√
Design scheme technical standard level	Design technical index level					√	
	Robustness of the design scheme					√	
	Innovative design guiding ideology					√	
	The overall arrangement and the difficulty of the structural system						√
	External environmental influence					√	
	Sustainable design				√		
	Cross-regional design				√		
	The advanced nature of survey equipment						√
	Data analysis and experimental sophistication					√	
Dynamic response of the structure	The natural frequency and main mode shape of the structural system					√	
	The stiffness index of the structure					√	
	The complexity of the applied load of the structure					√	
	Constraints of geological conditions on the structure					√	
	Setting standards for earthquake intensity					√	
	Structural element simulation analysis					√	
	Wind resistance stability index setting of the structure						√
	Structural Simulation Wind Tunnel Testing					√	
The difficulty of construction control	Engineering natural environment conditions				√		
	Structural system level					√	
	The degree of difficulty of construction						√
	The influence of geological conditions on construction				√		

	Application of advanced construction equipment			√	
	Diversity of construction plans			√	
	Innovation of construction organization design			√	
	Corporate standards for managers		√		
	Optimization of construction progress			√	
	Safety and quality systems			√	
	Civilized construction standards			√	
The complexity of the structural system	Project type (bridge, subgrade, tunnel, culvert, auxiliary structure, factory building, housing construction)			√	
	Main structure classification (extra-large, medium, small)				√
	The difficulty of structural modeling			√	
	Special structure installation scheme				√
The abusive nature of natural and human environments	Special weather effects		√		
	The complexity of the area where the project is located		√		
	Transportation impact			√	
	Urban, suburban, and remote areas disturbance elements			√	
	Community environmental impact	√			
	Construction Phase Project Management				√
Case study data robustness	Whether the design data is complete			√	
	Relevant research results retrieval		√		
	Construction organization design data			√	
	Various tests and test data		√		
	Completion data	√			
	Operation and maintenance data		√		

Notes: 0 = No Answer; 1 = Low; 2 = Average; 3 = Better; 4 = High; 5 = Perfect.

Sources: Own elaboration, based on part of data from (Cartaxo et al., 2011).

Eq.5.2

$$\tau_s^t = \frac{\tau_s^{\bar{a}} - \min_{1 \le i \le \tilde{a}} \tau_s^t}{\max_{1 \le i \le \tilde{a}} \tau_s^t - \min_{1 \le i \le \tilde{a}} \tau_s^t}$$

$\tau_s^{\bar{a}}$ is the average sensitivity coefficient; $\min_{1 \le i \le \tilde{a}} \tau_s^t$ is the minimum sensitivity coefficient;

$\max_{1 \le i \le \tilde{a}} \tau_s^t$ is the maximum sensitivity coefficient.

5.1. Basic situation of bridges

Basic term definitions: CSB refers to the structural system in which both ends of the stay cable are anchored on the tower, girder, or other carriers to form the standard bearing of the building, girder, and cable. Stay thread refers to the component that bears the tension and supports the girder. A cable tower refers to the element used to anchor or support the stay cable and transfer its cable force to the substructure. Girder is a component supported by stay cables and supports and directly bearing the traffic load transmitted by the bridge deck. The tower beam consolidation system is the structural system in which the tower beam is consolidated, and the support is set at the pier.

5.1.1. Single-pylon cable-styed bridge

China Jinma bridge is a super major bridge on Guangzhou - Zhaoqing Expressway. Its longitudinal length is 1,912.66m, and its width is 26.50m. The starting mileage is K18+749.610, and the ending mileage is K20+661.270. The bridge layout is 40×25m+25.8m+60m+2×283m+60m+25.8m+7×25m. The separated up-down 6-lane layout is adopted, and the road width is 2×(3.50+3.75+3.75)m. The design speed is 120km/h, calculated according to the automobile - super level 20 and checked by the trailer-120. The maximum longitudinal slope on the bridge is less than or equal to 3%; the convex and concave radius of the vertical curve is more than 17,000m and 6,000m, respectively. The transverse slope on the bridge is 1.5-2.0%. Its seismic intensity is 7 degrees. The bridge crosses the Xijiang River, and the clear width of the main and auxiliary navigable bridge openings is greater than or equal to 90m and 80m, respectively.The upper top width is greater than or equal to 70m and 60, respectively. The ship impact force borne by the pier of the main channel is 1,200 t along the water, 600 t along the bridge and, 110 t along the water of the auxiliary channel (Figure 5.1).

The approach bridge consists of 6 T-beams on the inner and outer sides, with 12. In terms of the inner and outer T-beams, the transverse net width is 218cm and 219.4cm, respectively; the thickness of the top plate is 15cm and 11-15cm, respectively; the thickness of the web plate is 16-40cm; the width of the bottom plate is 40cm. The girder height is 175cm, and the longitudinal length is 2478cm. The pier number of approach bridge is + 0 ~ + 9, 0~30, 30~31, 35~36 and 36~43. There are 49 spans and 490 T-beams in total (245 inner and 245 outer girders).

The main bridge adopts the design of a continuous rigid frame - a continuous girder system, which is a double cable plane concrete single-pylon

CSB. 32, 33, and 34 piers are consolidated with the girder, a single box and single chamber T- shaped rigid frame, with a height of 273.5 to 792.0cm, and the height span ratio is 1:21.9-1:7.6. The thickness of the top plate of the box girder is 24cm; the thickness of the web is 44 - 52cm; the thickness of the bottom plate is 30-70cm; the width of the base plate is 680cm; the cantilever lengths on both sides are 322.5cm and 645cm; the transverse slope is 1.5%. A 12Ø15.24 bottom loose steel strand and OVM15-12 anchorage are used longitudinally. The approach bridge and the main bridge are bored piles with pile caps, and anti-collision piers are designed for Pier 33. Case selection data analysis: according to Eq 5.1 and Eq 5.2 and 5.1.1 related information, the investigation of literature results, completed the data investigation and analysis of Table 5.1:

$\tau_s^1=\frac{0.914-0.800}{1.000-0.800}=\frac{0.114}{0.200}=0.57=57.0\%$

M_f^1 = (4+5+4+5+4+5+5)×(1±57.0%) = 32×1.57 = 50.24

$\tau_s^2 = \frac{0.800-0.600}{1.000-0.600}=\frac{0.200}{0.400} = 0.50 = 50.0\%$

M_f^2 = (4+4+4+5+4+3+3+5+4)×(1±50.0%) = 36×1.50 = 54.00

$\tau_s^3 = \frac{0.825-0.800}{1.000-0.800}=\frac{0.025}{0.200} = 0.125 = 12.5\%$

M_f^3 = (4+4+4+4+4+4+5+4)×(1±12.5%) = 33×1.25 = 41.25

$\tau_s^4 = \frac{0.780-0.600}{1.000-0.600}=\frac{0.180}{0.200} = 0.90 = 90.0\%$

M_f^4 = (4+5+3+4+4+4+3+4+4+4)×(1±90.0%) = 39×1.90 = 74.10

$\tau_s^5 = \frac{0.900-0.800}{1.000-0.800}=\frac{0.100}{0.200} = 0.50 = 50.0\%$

M_f^5 = (4+5+4+5)×(1±50.0%) = 18×1.50 = 27.00

$\tau_s^6 = \frac{0.680-0.400}{1.000-0.400}=\frac{0.280}{0.600} = 0.467 = 46.7\%$

M_f^6 = (3+3+4+2+5)×(1±46.7%) = 17×1.47 = 24.99

$\tau_s^7 = \frac{0.633-0.400}{1.000-0.400}=\frac{0.233}{0.600} = 0.388 = 38.8\%$

M_f^7 = (4+3+4+3+2+4)×(1±38.8%) = 20×1.39 = 27.80

$\overline{M_f^i} = \frac{\sum_{i=1}^{i=7} M_f}{i} = \frac{50.24+54.00+41.25+74.10+27.00+24.99+27.80}{7}$ = 42.77 (final case evaluation index data). $0.00 \le \overline{M_f^i} \le 50.00$, 42.77<50.00. The data showed that the case selection was high (grade 4~5).

Figure 5.2 shows the general layout of the JMB main bridge (CSB) project, which is mainly divided into three parts. See Table 5.2 for detailed descriptions. Two pairs of hanging baskets are installed on both sides of the 33# central tower

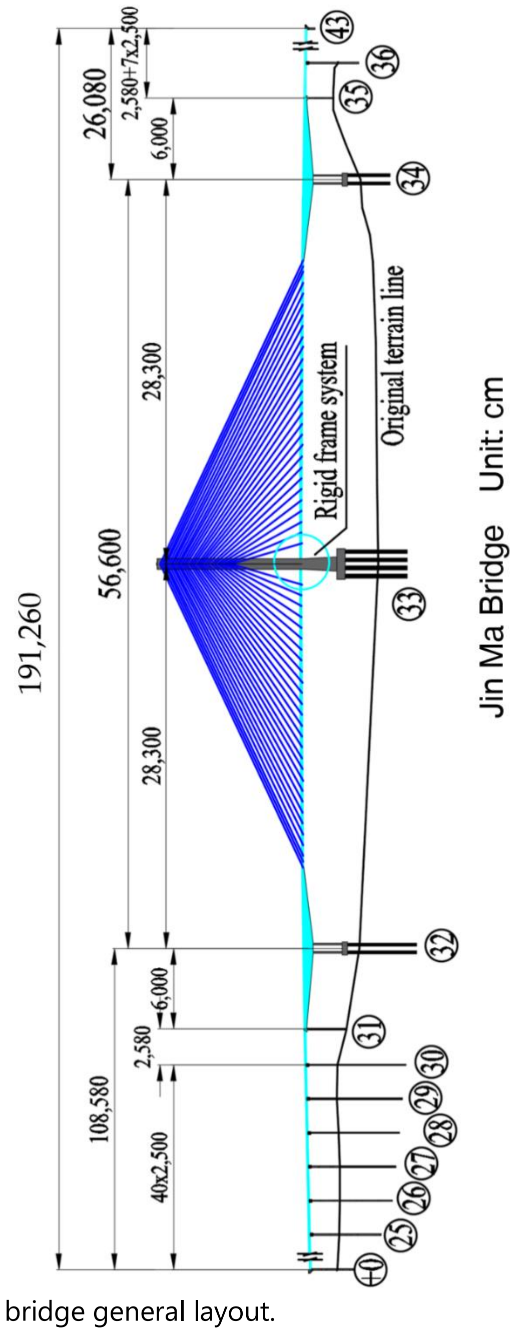
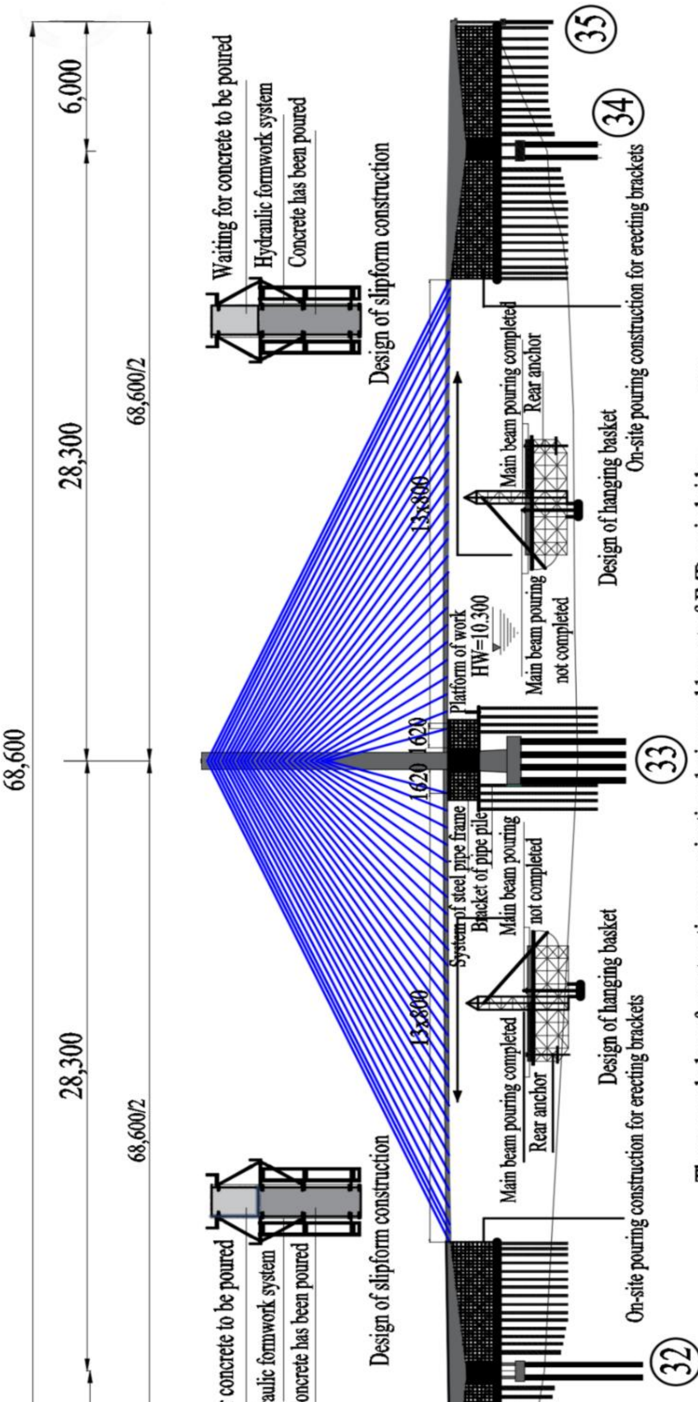


Figure 5.1. Jin Ma bridge general layout.

Sources: Own elaboration, based on part of data from design maps



The general plan of construction organization design and layout of JMB main bridge

Figure 5.2. Description of the construction organization and design of the JMB main bridge.

Sources: Own elaboration, based on part of data from design maps.

0# block during the construction of hanging baskets. After the construction of the cast-in-situ beam of 0# block is completed, other partition hanging baskets can be constructed. The length of the 0# block is 16.2m. The hanging basket shall be installed in two directions: 33# - 32# is divided into 13 sections, with a length of each area of 8m. The self-weight of concrete and hanging baskets is 3,600kN and 1,950kN, respectively. The direction of 33# - 34# is the same as above. The slip-form method is used to construct the central tower.

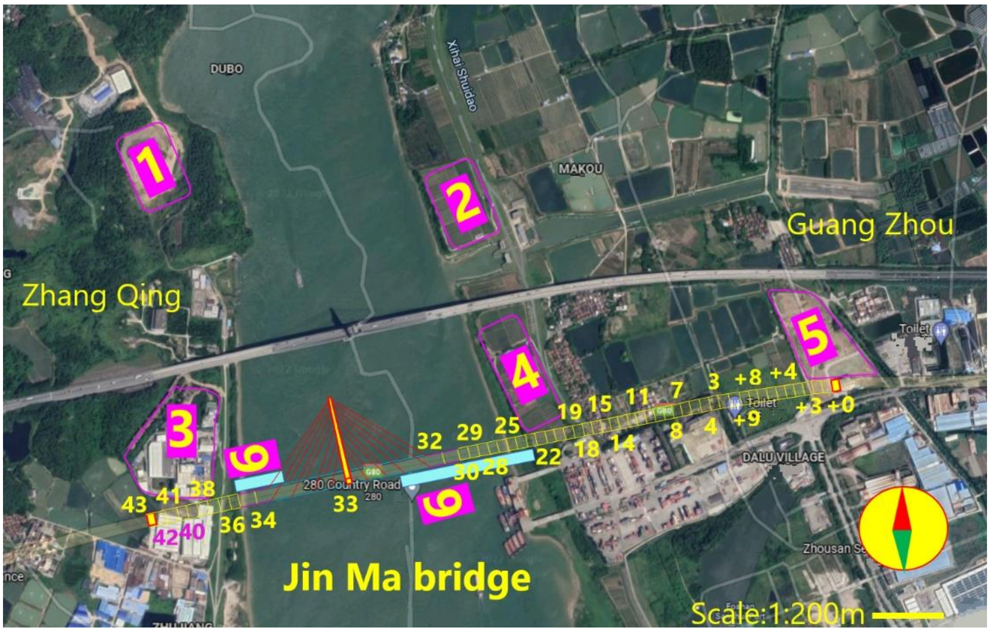
Table 5.2. The construction method of each component part of JMB

Number	Construction plan	Equipment and Materials
+0#~43#	The pile foundation is bored cast-in-place piles constructed with reverse circulation drilling equipment. The bearing platform and pier column are constructed with steel formwork vertical form, and the concrete is poured on-site.	Reverse circulation drilling equipment. Finished steel cage. Steel formwork. 25#, 30# concrete.
+0#~31# 35#~43#	The beam yard completes the prefabrication of the finished T beam, transports it to the construction site, and uses a bridge erection machine for on-site installation.	The project's general contractor will build a T-beam prefabricated beam yard and a concrete mixing station, equipped with equipment and facilities related to production, transportation, work, and life.
31#~34#	The central tower adopts the erection bracket, climbing form workflow operation, and on-site concrete pouring; the main beam adopts the hanging basket formwork installation flow operation, and the on-site concrete pouring construction.	Construction by ropes hanging basket method. Set of steel formwork. Steel pipe support system. Reinforcement and concrete.

Sources: Own elaboration, based on part of data from design maps.

The self-weight of the slip from the hydrostatic exalting system is 270kN. The construction load is 1.5kN/m^2, and the other additional loads are 20kN. The design time is from August 1994 to May 1995, with a total of 295 days; the construction time is from November 1994 to December 1999, with a total of 1880 days; the operation time is August 30, 2002; the service time is 7,094 days (as of January 2022).

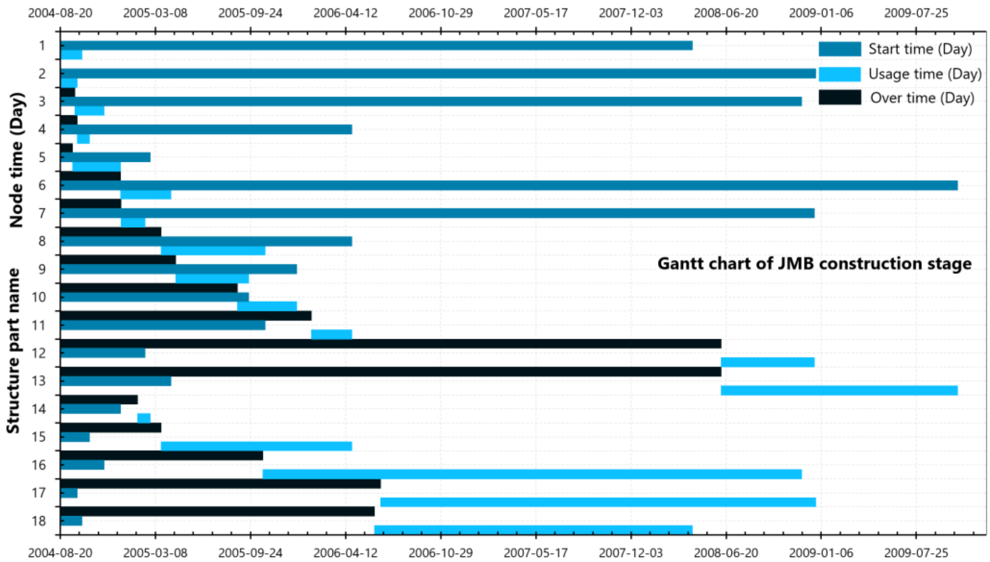
According to China's highway design and construction specifications, the construction unit should build a concrete mixing plant and a T-beam prefabrication plant (Rasheed et al., 2018). Regarding the original project organization design, design documents, construction contract, safety, and economic conditions, the construction scheme of temporary on-site facilities is planned and designed comprehensively (Figure 5.3). Main temporary facilities include project management and living areas, staff and construction personnel dormitories, a semi-finished product processing plant of reinforcement and formwork, one # and two # concrete mixing plants, a T-beam prefabrication, and a small component processing plant. The T-beam of the approach bridge is installed from the direction of +0# - 31#. The main bridge must have the traffic capacity of beam transport trucks before installing 31# T-beam to ensure that 80 T-beams from 35 # to 43 # can be installed smoothly.



Notes: 1. Project management department area; 2. Staff accommodation and living area; 3. Concrete Mixing Station NO.1; 4. Rebar semifinished products and form work processing factories; 5. Concrete Mixing Station No. 2; Manufacturing T beam factory; Prefabrication factory for small components; 6. Temporary steel bridge.

Figure 5.3. The general plan of the temporary facilities of the project.

Sources: Own elaboration, based on part of data from google maps.



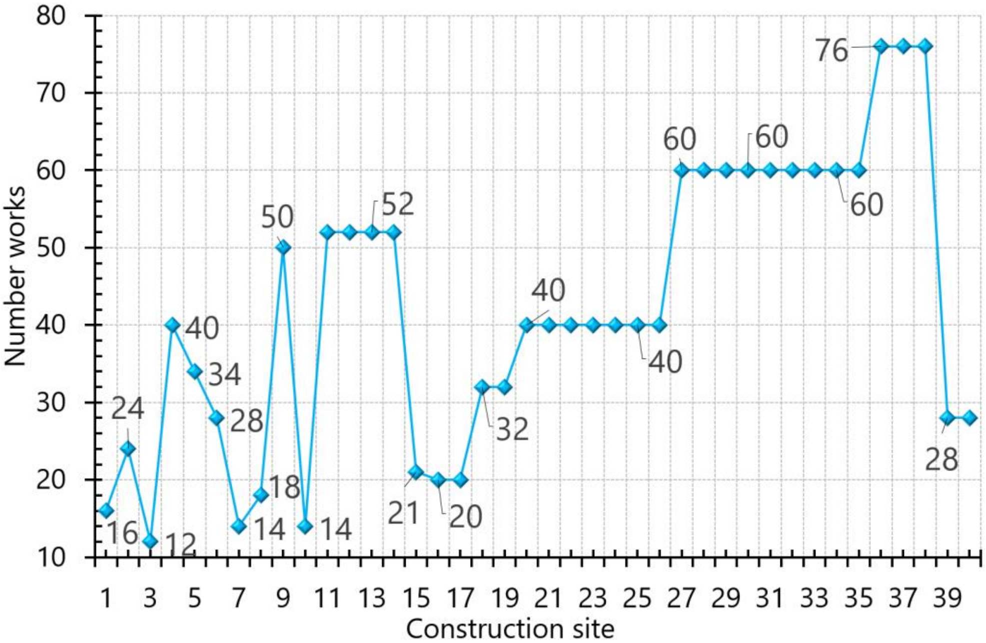
Notes: 1. Prepare start; 2. Installation of temporary facilities is complete; 3. 0#-31# pile foundation construction; 4. 35#-43# pile foundation construction; 5. 32#-34# pile foundation construction; 6. 0# bearing platform and abutment construction; 7. 31# bearing platform construction; 8. 0#-31# pier column construction; 9. +1#-42# bearing platform and abutment construction; 10. 33# bearing platform and abutment construction; 11. +0#-31#, 35#-43# bearing pad stone construction; 12. 0#-31#, 35#-43# bridge deck auxiliary facilities installation; 13. 0#-43# completion acceptance stage; 14. 32#-34# bearing platform construction;15. 33# cable tower column construction; 16. 32#-34# girder construction; 17. 32#-34# stay cable construction; 18. +0#-31#, 35#-43# T beam production and installation.

Figure 5.4. JMB's construction process gantt chart.

Sources: Own elaboration.

Figure 5.4 is the Gantt chart at the construction stage. There are seven construction teams in total, including the first shift, second shift, third shift, and fourth shift of the main body. The beam factory is the branch organization of the project and is responsible for the transpiration and installation of all 0# - 43# T-beams. Three operation teams are arranged for the pile foundation and shall leave the construction site after the construction of 202 pile foundations and the construction task is completed. There are 55 project management personnel, 238 long-term construction workers, and 142 short-term temporary facility installation and pile foundation workers (Figure 5.5).

The construction process is implemented following the streamlined operation, and the construction tasks of each work shift are implemented under the construction schedule of the project management department. The construction progress can be postponed due to missed work or special weather reasons, but the construction progress plan on key lines is strictly implemented and cannot be delayed.



Notes: 1. Prepare start; 2. Entry time; 3. Step planning; 4. Project department construction; 5. Construction of N0.1 mixing plant; 6. Construction of N0.2 mixing plant; 7. Staff accommodation and living areas; 8. Semi-finished product processing plant; 9. T beam prefab factory; 10. Small component factory; 11. 32#-34# steel bridge installation; 12. 32# enclosure construction; 13. 33# enclosure construction; 14. 34# enclosure construction; 15. 32#, 33#, 34# pile foundation construction; 16. 0#-26# site leveling; 17. 36#-43# site leveling; 18. 0#-31# pile foundation construction; 19. 35#-43# pile foundation construction; 20. 0#-31#

platform and bridge abutment construction; 21. 0#-32# pier construction; 22. 0#-33# pedestal and pads construction; 23. 35#-43# platform and bridge abutment construction; 24. 35#-43# pile construction; 25. 35#-44# pier construction; 26. 35#-43# pedestal and pads; 27. 32#, 33#, 34# platform construction; 28. 32#, 34# bearing platform construction; 29. 32#, 34# pier construction; 30. 32#, 34# pedestal and pads construction; 31. 32#, 34# main beam construction; 32. 33# main tower construction; 33. 33# main beam construction; 34. 33# cable installation; 35. 32#, 33#, 34# tensioned construction; 36. T beam production; 37. 0#-31# T beam transportation and installation; 38. 35#-43# T beam transportation and installation; 39. 0#-43# T bridge decking and ancillary construction; 40. 0#-43# T preparation for completion acceptance.

Figure 5.5. Time node and construction personnel arrangement for each sub-item project.

Sources: Own elaboration.

5.2. Sustainable comprehensive assessment of JMB

Firstly, the analysis of sustainable data sources is carried out according to the original design model. The LCC research model has been discussed in the theoretical part of 3.1. The service time of the case bridge is 23 years (as of 2022), and the service cycle agreed according to the design drawings is 100 years. The bridge is not in the demolition stage, so the cost at the demolition stage is zero in the case analysis.

5.2.1. Analysis of LCC data

According to Table 5.3, the final total cost of JMB in the planning and construction stage is 294.481,1 million CNY, which includes three parts: quantities of approach bridge +0# - 31# and 35# - 43#, that of 31# - 32# and 34# - 35# T-beams of the main bridge and that of 32# - 34# CSBs.

$$C_{\mathrm{S-JMB}} = 16.75 \times 1.913 \times 3 = 961{,}300 \text{ CNY}$$

The expressway survey and design cost standard in China shall be implemented in accordance with the charging standard of document [2002] No. 10 issued by the Ministry of Construction of China (R. Wang et al., 2021), that is, highway survey cost = highway survey base price cost × design quantities × adjustment coefficient. The base price of charging is 167,500 CNY/km, and the additional adjustment coefficient is taken according to the degree of project difficulty, with a range of 2~3. JMB is a cooperative system bridge between large-scale concrete CSB and T-shaped rigid frame, with high construction difficulty coefficient of 3. Engineering design fee = (design base price fee) × professional adjustment coefficient × adjustment coefficient of engineering complexity and difficulty × additional adjustment coefficient + other design charges) × (1 ± floating amplitude value).

$$C_{\mathrm{D-JMB}} = (810.4\times0.9\times1.15)\times(1\pm1.65\%) = 8{,}526{,}000 \text{ CNY}$$

Table 5.3. The total cost of the planning and construction phase of JMB

Number	Name	Calculation method	JMB (CNY)
1	Labor Costs	Quota* working days	15 293 200.00
2	Direct Costs	Labor + Material+ Mechanical	199,738,091.29
3	Equipment Purchase Costs	1.899%*1	3,793,026.35
4	Measures Costs	4.381%*1	669,995.09
5	Enterprise management fees	4.143%*2	8,275,149.12
6	Regulation fees	30.65%*1	4,687,365.80
7	Profits	7.42%*5	614,016.06
8	Taxes	10%*(2+...+7)	21,777,764.37
9	Special expenses	Standard+1.5%*(2+...+7)	9,818,631.12
10	Compensation fees for land use and demolition	0.06381*(2+...+9)	15,912,557.44
11	Other costs of engineering construction	3.14%*2	6,271,776.07
12	Preparation cost	3%*2	5,992,142.74
13	Loan interest during construction period	6.1%*(2+...+12)	16,930,581.44
14	The basic cost of the project	(1+...+13)	294,481,096.91

Sources: Own elaboration, based on part of data from (R. Wang et al., 2021).

The cost of expressway maintenance and opreation stage is affected by many external uncertain factors, such as the dynamic change of maintenance plan, the complexity of the natural environment, material deterioration, etc. Therefore, it is more scientific and practical to take the average maintenance costs in China's expressways as the research basis of this thesis. According to the data released by the Ministry of Transport of the People's Republic of China, the maintenance costs include: the sum of the expenses for daily minor repair and

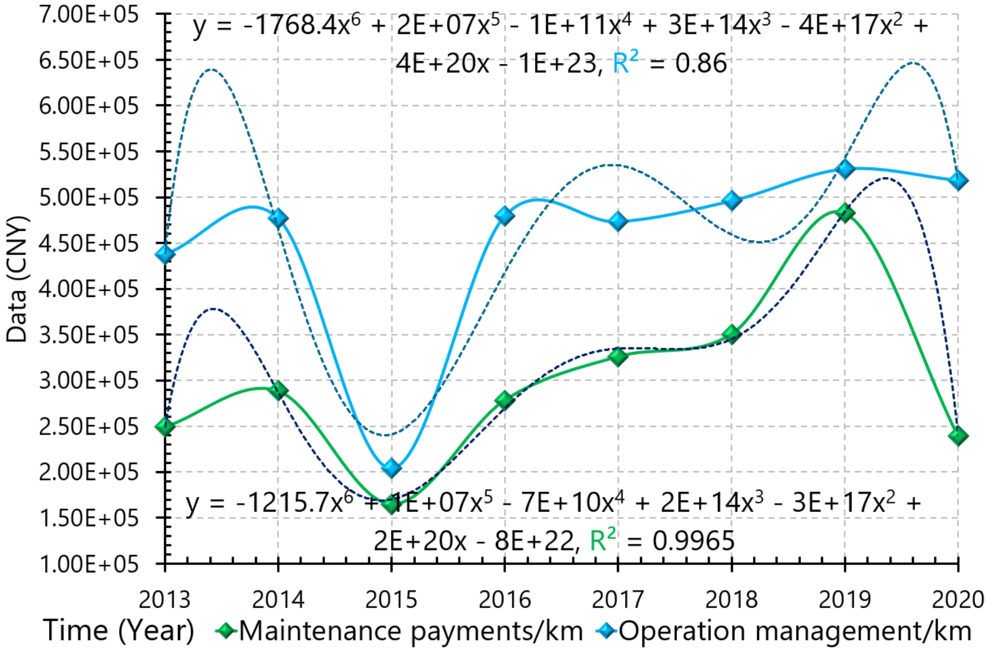


Figure 5.6. China's Chinese Ministry of Communications road maintenance data.

Sources: Own elaboration.

maintenance (including the salary of maintenance personnel), large and intermediate overhaul works, preventive maintenance, purchase of maintenance facilities and equipment, maintenance inspection and detection, emergency maintenance, transformation and maintenance of electromechanical system, production and lighting power. The service and management costs include the sum of the expenses for charging business, daily management, road administration, and overload control (Yao et al., 2020). The price from 2013 to 2020 was 749,612.65 CNY/km/year (Figure 5.6).

$$C_{U-\mathrm{JMB}} = 749612.65 \times 1.913 \times 23 = 32{,}982{,}206.99 \text{ CNY}$$

$$C_{L-\mathrm{JMB}} = 294{,}481{,}096.91 + 961{,}300 + 8{,}526{,}000 + 32{,}982{,}206.99 = 336{,}950{,}603.87 \text{ CNY}.$$

The preparation and brief stage costs are calculated in the construction stage because the investor participates in and supervises all projects during the whole construction. As JMB has not reached the design agreed life, the cost of the demolition stage is zero. According to the analysis data of LCC and the random model of 3.1.4 emergencies, the discrete calibration coefficient (3.15) is added in the maintenance stage, which is obtained from the analysis of mathematical model in Eq.3.1.4.

5.2.2. Analysis of LCA data

OpenLca1.10.3 software is selected for LCA analysis of the case bridge, and

Table 5.4. LCA of JMB

Code	Name	Unit (eq)	Number of LCA (JMB)
1	Abiotic depletion	kg Sb	148,467.00
2	Acidification	kg SO_2	138,664.00
3	Eutrophication	kg PO_4	37,698.20
4	Fresh water aquatic ecotax	t 1,4-DB	12,574.60
5	Global warming (GWP100)	t CO_2	23,468.10
6	Human toxicity	t 1,4-DB	33,029.50
7	Marine aquatic ecotoxicity	1000 t 1,4-DB	18,891.60
8	Ozone layer depletion (ODP)	kg CFC-11	1.0604
9	Photochemical oxidation	kg C_2H_4	7,928.58
10	Terrestrial ecotoxicity	kg 1,4-DB	133,545.00

Sources: Own elaboration.

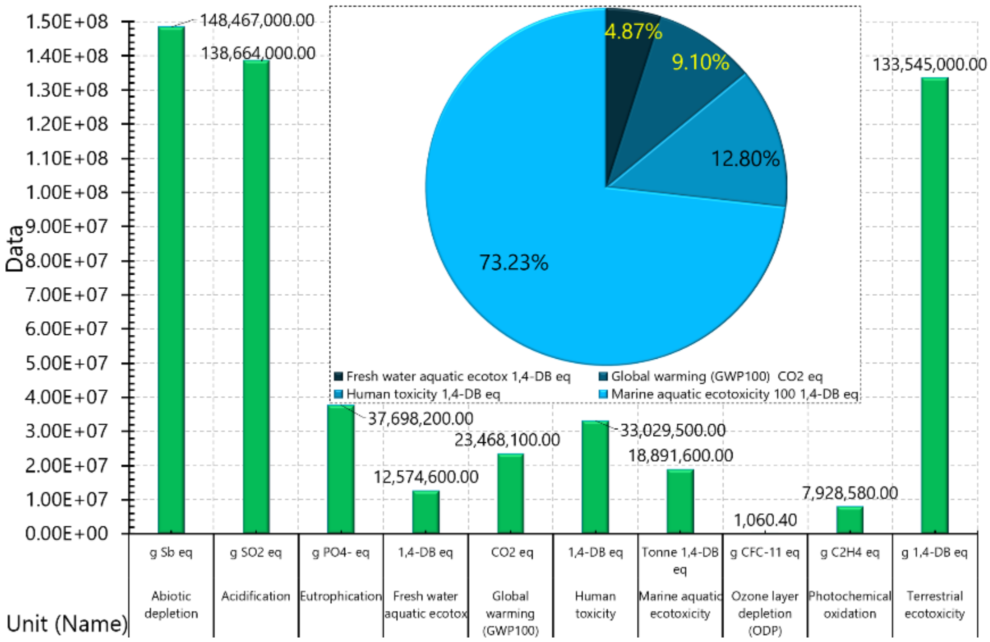


Figure 5.7. LCA analysis data of JMB.

Sources: Own elaboration, and anaiysis used the excel software.

the conclusion after the research is the impact data in the whole life cycle of the bridge. The database used in LCA analysis has a full LCA and sustainability.

In JMB data, the number of processes is 23,060 and the number of process links is 414,103. After software analysis, the connected graph and calculate are feasible. See Table 5.4 for the analysis data.

According to Figure 5.7, marine aquatic ecology is 18.891,6 million t, accounting for 99.63% of the total, indicating that the construction industry severely polluted the marine aquatic ecology. Human toxicity damage ranks second, directly related to the physical and mental health of the project participants. The high rate of work-related injuries, occupational diseases, and fortuitous casualties has become one of the most dangerous working environments in the construction industry (Asadzadeh et al., 2020). GWP100 ranks third, the most severe source of environmental pollution. In particular, greenhouse gas emissions in developing countries and economic recovery regions have led to the periodic rise of global temperature by 1.5°.

The data ranked in the top four accounts for 99.99% of the total emissions (18.96 million t) of the project.

5.2.3. Analysis of SIA data

At present, SIA data research is a weak link to SD. See Chapter 3 for a detailed analysis. SIA has the most significant impact on social and community personnel. SCIA data can be obtained synchronously after analyzing LCA data. Seven critical indicators of core analysis are marked in 3.3.2. To comprehensively and accurately describe the impact of bridge engineering on the community, the scope of hands is expanded, and all 37 influencing factors are analyzed (Table 5.5).

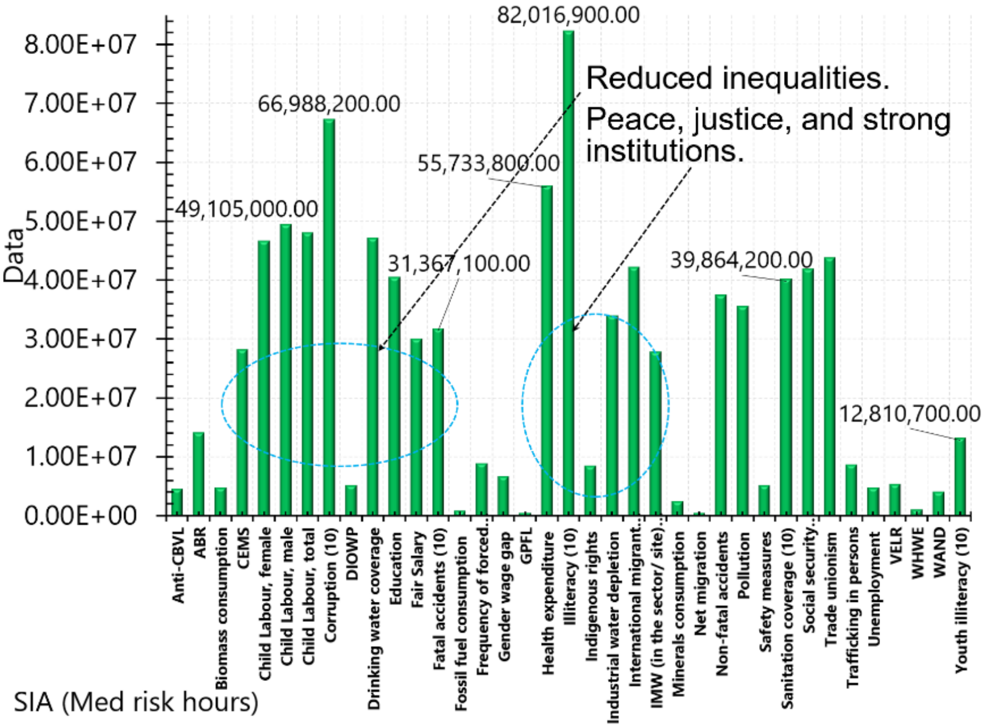
The total SIA data are 326.16 million Mrh, of which the top six are Illiteracy = 820,169,000, Corruption = 669,882,000, Sanitation coverage = 398,642,000, Fatal accidents = 313,671,000, International migrant workers (in the sector/ site) = 275,148,000, Youth illiteracy = 128,107,000. Thirty seven indicators have discreteness, and most of the data are concentrated in the two indicator ranges of reducing inequality and peace, justice and powerful institutions.

Table 5.5. SIA of JMB

Code	Name	SIA (Mrh)
1	Anticompetitive conduct or monopoly legislation	4,243,270
2	Association and bargaining rights	13,723,200
3	Biomass consumption	4,347,280
4	Certified environmental management system	27,916,100
5	Child Labour, female	46,289,100
6	Child Labour, male	49,105,000
7	Child Labour, total	47,714,500
8	Corruption	669,882,000
9	Dalys due to air and water pollution	4,776,030
10	Drinking water coverage	46,812,100
11	Education	40,209,900
12	Fair Salary	29,696,400
13	Fatal accidents	313,671,000
14	Fossil fuel consumption	465,302
15	Frequency of forced labour	8,517,330
16	Gender wage gap	6,291,390
17	Goods produced by forced labour	5,637.11
18	Health expenditure	55,733,800
19	Illiteracy	820,169,000
20	Indigenous rights	8,100,650
21	Industrial water depletion	33,665,500
22	International migrant stock	41,930,300
23	International migrant workers (in the sector/ site)	275,148,000
24	Minerals consumption	2,081,600
25	Net migration	62,026.8
26	Non-fatal accidents	37,194,000
27	Pollution	35,260,200
28	Safety measures	4,814,630
29	Sanitation coverage	398,642,000
30	Social security expenditures	41,571,500
31	Trade unionism	43,488,000
32	Trafficking in persons	8,289,020
33	Unemployment	4,386,300
34	Violations relevant laws	4,966,480
35	Work times/per/week	631,646
36	Workers/natural disasters	3,653,270

37	Youth illiteracy	128,107,000

Sources: Own elaboration, and anaiysis used the openLCA software.

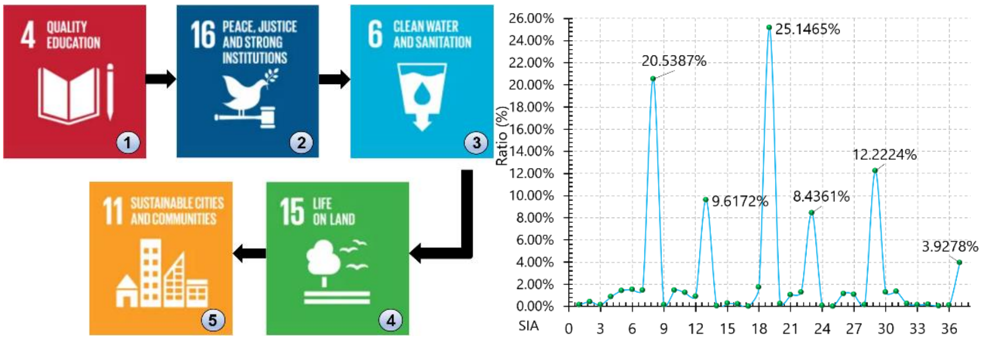


Notes: Anti-CBVL = Anticompetitive conduct or monopoly legislation; ABR = Association and bargaining rights; CEMS = Certified environmental management system; DIOWP = Dalys due to air and water pollution; GPFL = Goods produced by forced labour; VELR = Violations relevant laws; WHWE = Work times/per/week; WAND = Workers/natural disasters (the above abbreviations only apply to Figure 5.8).

Figure 5.8. SIA analysis data of JMB.

Sources: Own elaboration.

SIA study focuses on the 17 UN sustainability goals, explained in 3.1. For JMB research, the top six targets are shown in Figures 5.8 and 5.9. Education should be in the first place, which has become the most potent force of change and reform for an important tool to achieve a sustainable future. All regions, countries, and institutions should deliberately, continuously, and strategically integrate and mainstream sustainable education (Agbedahin, 2019). The top six impact data accounts for 79.89% of total emissions, which is 260.56 million mrh.



(a) (b)

Figure 5.9. JMB's SIA UN goals.

Sources: Own elaboration.

5.3. Topology optimization assessment of JMB

In 5.1, it is analyzed that the ultimate goal of bridge optimization is to reduce the amount of material used, which can be achieved by redesigning the geometric dimensions of bridge components. The premise of completing this study is to meet the original bridge's primary technical standards and bridge load specifications. All bridges are in regular service. In this thesis, the latest design specifications and standards for highway bridges and culverts in China (*JTG D60-2015*, *JTG/T D65-01-2007*, *JTG/T 3365-01-2020*). They are used to analyze the load to avoid overload and interference of uncertain factors and meet the requirements of strength, stiffness, stability, and durability within the design cycle of 100 years.

5.3.1. Analysis of loading

In *JTG D60-2015*, it is stipulated that there are four kinds of design forces of bridges and culverts, including permanent action, variable action, accidental action, and seismic action. See Table 5.6 for the analysis of technical standards for bridge design.

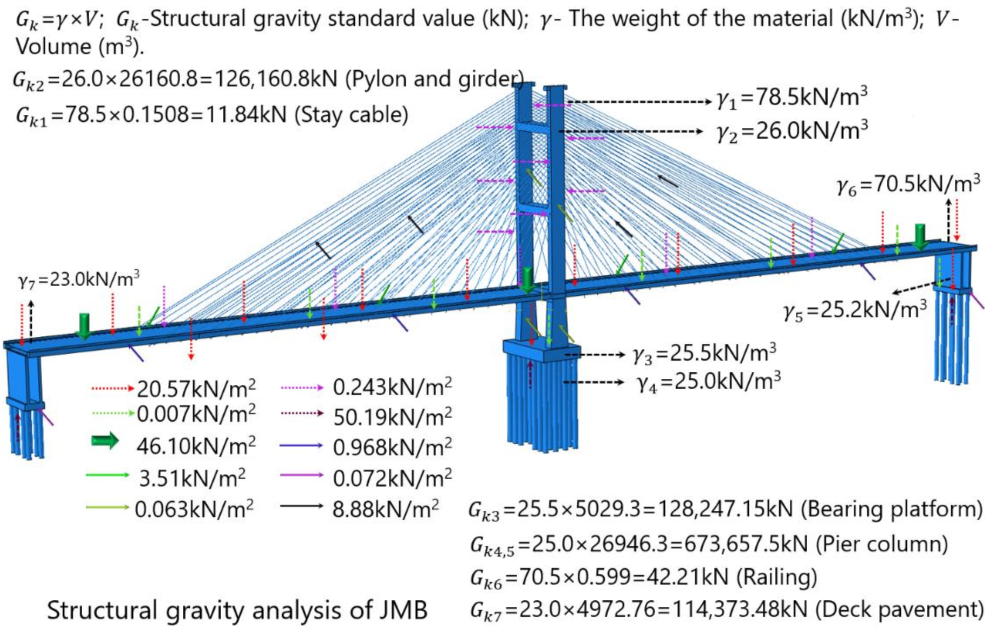
5.3.1.1.Permanent action

Based on the statically indeterminate concrete structure and the combination of steel and concrete, the shrinkage and creep of concrete are considered for the CSB. In the calculation, it is assumed that the creep has a linear relationship with the concrete stress at $[\sigma(t)]= [D] \times [\xi_C(\sigma,t)]$, σ is the stress at t (Colajanni et al., 2021). According to the technical indicators of the case bridge, ξ_C calculated value range is (0.571~0.667), $\sigma(t) \in$ (287~334kN).

Water buoyancy analysis: in the checking calculation of the bearing capacity of the bridge foundation, considering the influence of the water level on the water buoyancy of the bottom surface of the bridge pier and abutment, two JMB water levels are designed, that is, the warning water level is SW = 12.040m and the maximum water level is HW = 10.300m. In both cases, 32#, 33#, and 34# pile foundations, pile caps, and pier columns are within the water level, so the water buoyancy needs to be calculated.

$F_{JMB} = \gamma \times V$ = 9.8kN/m^3×(9.52×3.0×21.52×2+22.5×6.15×37.5) = 62,899.19KN

Wenqing Wu (2018) developed a set of integrated system to monitor the change of foundation displacement of long-span bridge, and selected the double-pylon CSB to carry out two years of monitoring, and finally obtained the average foundation displacement data of 0.5mm. When characterizing the response, the comprehensive effects of various loads are considered. The despla-



Structural gravity analysis of JMB

Note: Figure 5.10 is the load diagram of JMB. It represents the load distribution, location and size.

Figure 5.10. Structural gravity analysis of JMB.

Sources: Own elaboration, and anaiysis used the Abaqus software.

cement studied in this thesis is much larger than the data, which is 0.8mm.

5.3.1.2. Variable action

Variable action is a vital part of bridge design. The load mainly includes vehicle, movable, wind, ambient temperature, and other variable loads (Table 5.6; Figure 5.10). The designed bridge is a Class I expressway, with a uniformly distributed load of 10.5kN/m^2, a bridge span of more than 50m, and a concentrated load of 10.5KN/m^2. The vehicle load is designed according to the automobile - super level 20 and trailer-120, and the total weight is less than 45 t/vehicle. The value is 13.33kN/m^2. The bridge is designed with six lanes, with the longitudinal and transverse reduction coefficients being 0.96 and 0.55, respectively.

Vehicle impact load = standard value of vehicle load × impact coefficient = 34.33 × f^1 = 34.33 × 0.05 = 1.72kN/m^2 (JMB).

Vehicle load centrifugal force = vehicle load × centrifugal force coefficient = 34.33 × $\frac{v^2}{127R}$ = 34.33 × $\frac{80^2}{127\times7000}$ = 0.25 kN/m^2 (JMB). The designed bridge has four lanes in the same direction, and the vehicle braking force is 2.68 times 165kN, namely 442.2kN.

Vehicle fatigue load = 0.7 × Concentrated load + 0.3 × Uniformly distributed load = 0.7×10.5+0.3 ×10.5 = 10.5kN/m^2.

Wind load is the crucial part of bridge wind resistance design, which is not the focus of this thesis, but the influence of wind load on the CSB must be comprehensively analyzed (Jiang et al., 2020). Several basic research principles are formulated: a) During the design service life of the bridge, there will be no destructive self-excited divergent vibration in the structure when the maximum wind speed occurs in the bridge construction area. b) Under the design load or composite load, the bridge should have sufficient strength and stiffness without static instability. c) The amplitude of non-destructive wind-induced vibration of the bridge should meet the requirements of structural fatigue, driving safety, and comfort. d) Aerodynamic, structural and mechanical measures can improve the wind resistance of the bridge. e) It is unnecessary to analyze the wind stability checking calculation and field wind load force simulation because the wind tunnel test will be conducted.

Transverse static gust load on girder = $\frac{1}{2} \times \rho \times v_g^2 \times c_H \times H$ = 0.5×1.25×28^2×1.975,4 = 967.95N/m.

Maximum span of bridge is more than 200m. JMB longitudinal wind load = $\frac{1}{2} \times \rho \times v_g^2 \times c_f \times s$= 0.5×1.25×28^2×0.02×18,179 = 178,154.2 N/m.

Static wind load of pier = $\frac{1}{2} \times \rho \times v_g^2 \times c_H \times A_n$ = 0.5×1.25×28^2×1.7×40 = 33,320 N/m; Tower = $\frac{1}{2} \times \rho \times v_g^2 \times c_H \times A_n$ = 0.5×1.25×28^2×1.7×24 = 19,992 N/m; Stay cable $\frac{1}{2} \times \rho \times v_g^2 \times c_H \times A_n$ = 0.5×1.25×28^2×1.7×10.66 = 8,879.78 N/m.

Table 5.6. Loading data for JMB

Number	Tope	Name	Design standard (kN)
			JMB
1	Permanent action	Structural gravity	1,042,492.98
2		Pre-stress	12,300.344
3		Soil gravity	/
4		Soil lateral pressure	/
5		Concrete shrinkage、Creep	287~334
6		Water buoyancy	62,899.19
7		Foundation displacement	0.8mm
8	Variable action	Vehicle load	34.33kN/m^2
9		Vehicle impact force	1.72kN/m^2
10		Centrifugal force of vehicle load	0.25kN/m^2
11		Vehicle braking force	442.2
12		Vehicle fatigue load	10.5kN/m^2
13		Lateral static gust load	967.95N/m
14		Longitudinal static gust load	178,154.2 N/m
15			33,320 N/m
16		Lateral static gust load	19,992 N/m
17			8,879.78 N/m
18	Accidental action	Vehicle impact effect	/
19		Earthquake effect	/

Sources: Own elaboration.

JMB is located in the subtropical monsoon and subtropical continental zones, with an annual average temperature of 22.2℃. The yearly variation temperature of the two bridges is ±12℃. The primary material of the CSB is reinforced concrete, with a linear expansion coefficient of 0.000,012/℃. According to the comprehensive analysis, the influence of temperature stress factors is low, which will not be considered (Z. Liu et al., 2020).

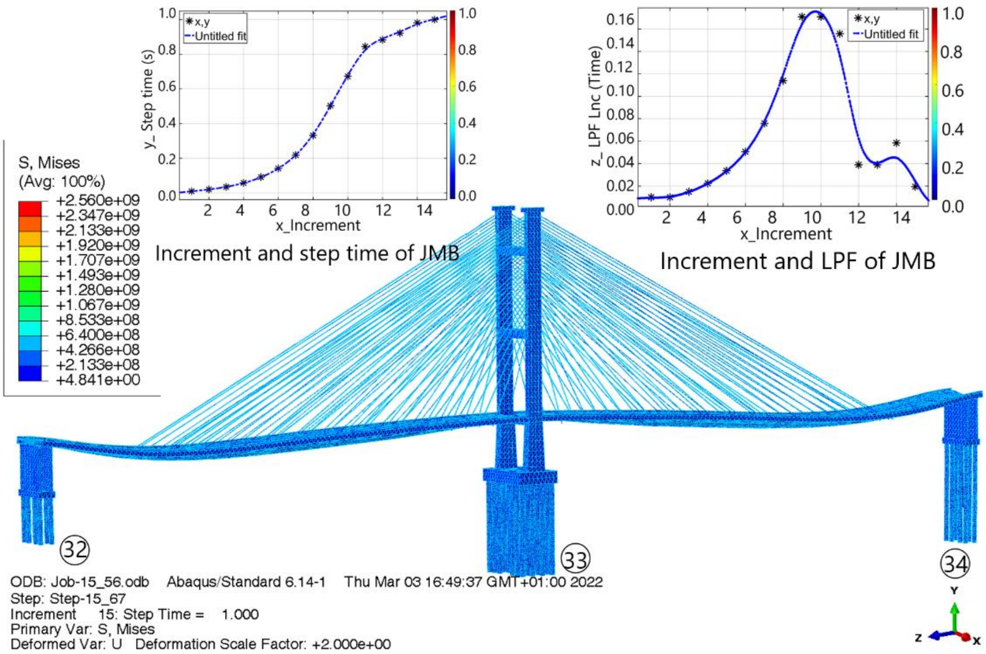
According to the "Earthquake intensity zoning map of China" and the *Evaluation Report of Seismic Safety for Engineering Sites* completed by the Institute of Seismology, CEA (China Earthquake Administration), the primary intensity of the area where the JMB is located is grade VI, and the geological structure is relatively stable (B. Wei et al., 2020), so don’t required analysis.

Table 5.6 shows the stress distribution of JMB under load, of which structural gravity and vehicle load are the leading indicators affecting structural stability and durability.

5.3.2. Analysis of finite element

Relating to or affecting the structure, finite element analysis is the essential work of TO; which can analyze the stress, strain, displacement, and energy distribution and constraints in the structure under the composite load to ensure

5.3.2.1. JMB (Main bridge)



Finite element analysis 3D solid model of JMB

Figure 5.11. Finite model analysis of JMB (see additional data for other analysis).

Sources: Own elaboration, and anaiysis used the Abaqus software.

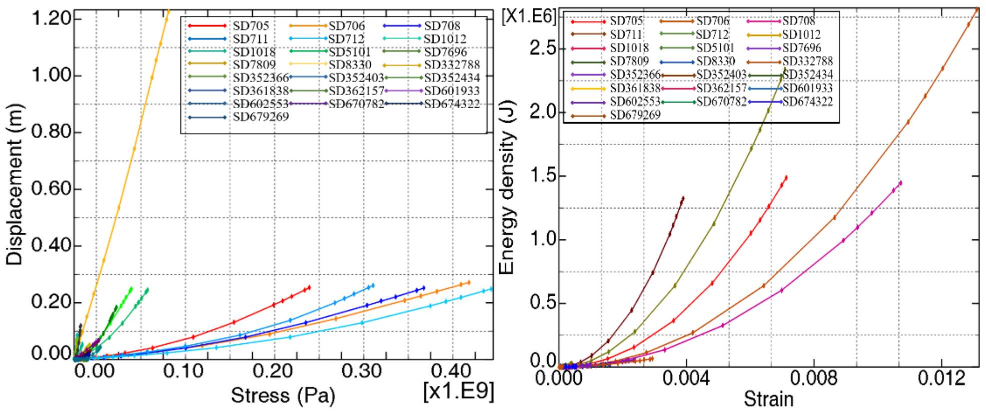
no damage to the main structure and meet the optimization goal of minimizing volume in the process of TO.

There are 350,109 finite elements in JMB, with 0 analysis errors and 66,004 analysis warnings, accounting for 18.8524% of the total. The increment in finite element analysis is 15, and the time of the current analysis step is 1s. See Figure 5.11 for incremental effort and total iteration time. According to theoretical models in 4.2.1 and 4.2.2, the changes of four parameters of practical constraints and stress in JMB structure under load are analyzed by components. The data validity and discreteness of each element are analyzed by Matlab software, laying the assessment standard and judgment foundation for TO.

The lower part of the 32# girder is used as a single research component, and 22 groups of elements are selected at each part to carry out data analysis (elements selected must cover the maximum and minimum stresses and be effective) (Figure 5.12).

Stress ranking are 467,948,544Pa (712 element) → 442,849,696Pa(706 element) → 392,112,704Pa (708 element) → 335,408,352Pa (711 element) → 263,950,496Pa (705 element).

The displacement ranking are 0.272m (706 element) → 0.261m (711 element) → 0.253m (705 element) → 0.252m (708 element) → 0.249m (712 element) (Figure 5.12-a)..



(a) (b)

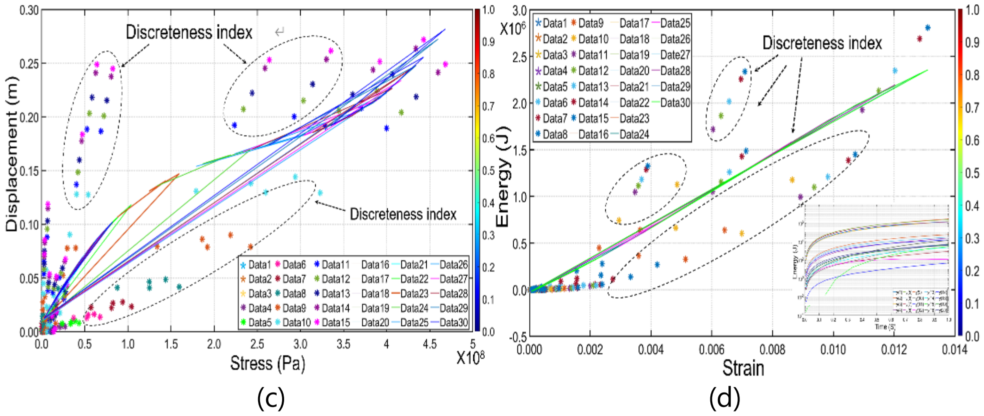


Figure 5.12. Number analysis of 32#. (a) stress and displacement. (b) stain and energy density. (c) finite analysis of stress and displacement. (d) finite analysis of strain and energy density.

Sources: Own elaboration, and anaiysis used the Abaqus software.

Monitoring point location: 712 element →Located at the top surface of the left line 32# support; 706 element → Located at the top surface of the right line 32# support; 708 element → Located at the top surface of the left line 32# support; 711 element → Located at the top surface of the right line 32# support; 705 element → Located at the top surface of the right line 32# support.

Strain ranking are 0.013,11 (706 element) → 0.010,71 (708 element) → 0.007,1 (705 element) → 0.007,09 (712 element) → 0.003,89 (711 element).

Energy density ranking are 2,808,464.75J (706 element) → 2,337,447.25J (712 element) → 1,487,248.88J (705 element) → 1,447,712.5J (708 element) → 1,324,917.5J (711 element) (Figure 5.12-b).

Discreteness analysis: under the action of the bridge girder and other structures, the stress of the 32# component is redistributed in the form. First, it is necessary to judge whether TO conditions are met by the mathematical model. The analysis data include 22 stress and displacement, strain, and energy groups. After fitting, Figure 5.12-c shows that the data have poor discreteness and constraint, and many stress and displacement elements are outside the fitting area. After several iterations of finite element optimization, the energy of 32# in the structure is redistributed and balanced along the constraint boundary of each element under the action of design constraint variables, forming a new coupled optimal constraint combination model.

However, some features do not show the discrete state of degrees of freedom in the energy dissipation equivalent load distribution, which is in the discrete part of TO. Figure 5.12-d shows the energy distribution of the structure, and the energy is more convergent than the stress. After the load is transmitted to the support, the structure's energy is redistributed in 1S. The power of the 1,012 elements is 0, which is located on the top surface of the outer side of the 32# right line pile cap, indicating that the energy dispersion and resolution in these areas are over. It can also be found that the transmission direction of energy in the same medium (reinforced concrete) is consistent with the linearity. It is a sudden transmission in 0.2S, grows slowly in the 0.2S~1.0S time zone, and tends to be stable, indicating that the energy transmission has a transient value and high convergence rate.

Judgment conclusion: Through the comprehensive evaluation in Figure 5.12, there are redundant structures in 32#, which can be optimized locally again in TO.

33# and main tower are the consolidation system of tower beam pier, which is analyzed as a whole. 43 groups of elements are set as stress monitoring points.

The stress ranking are 43,752,416Pa (890 element) → 35,299,404Pa (735 element) → 27,496,540Pa (729 element) → 18,452,268Pa (6652 element) → 18,174,478Pa (542750 element).

The displacements are: 0.033m (890 element) ↔ 0.032,8m (735 element) ↔ 0.032m (729 element) ↔ 0.038m (6652 element) ↔ 0.039m (542750 element).

Monitoring point location: 890 element → Located at consolidation position of left line main tower and girder; 735 element → Located at consolidation position of left line main tower and girder; 729 element → Located at consolidation position of right line main tower and girder; 6652 element → Located at 1/5H above the contact surface between the left line main tower and girder; 542750 element → Located at 1/8H above the contact surface between the right line main tower and girder)(Figure 5.13-a).

The robustness of the analysis is enhanced in the Strain data, and 50 groups elements are monitored.

The strain ranking are 0.00,031 (347885 element) → 0.00,031 (551539 element) → 0.00,018 (347683 element) → 0.000,17 (271 element) → 0.000,17 (280 element).

The energy density ranking are 307.55J (347885 element) ↔ 2,485.62J (551539 element) ↔ 305.20J (347683 element) ↔ 420.35J (271 element) ↔ 2,033.16J (280 element).

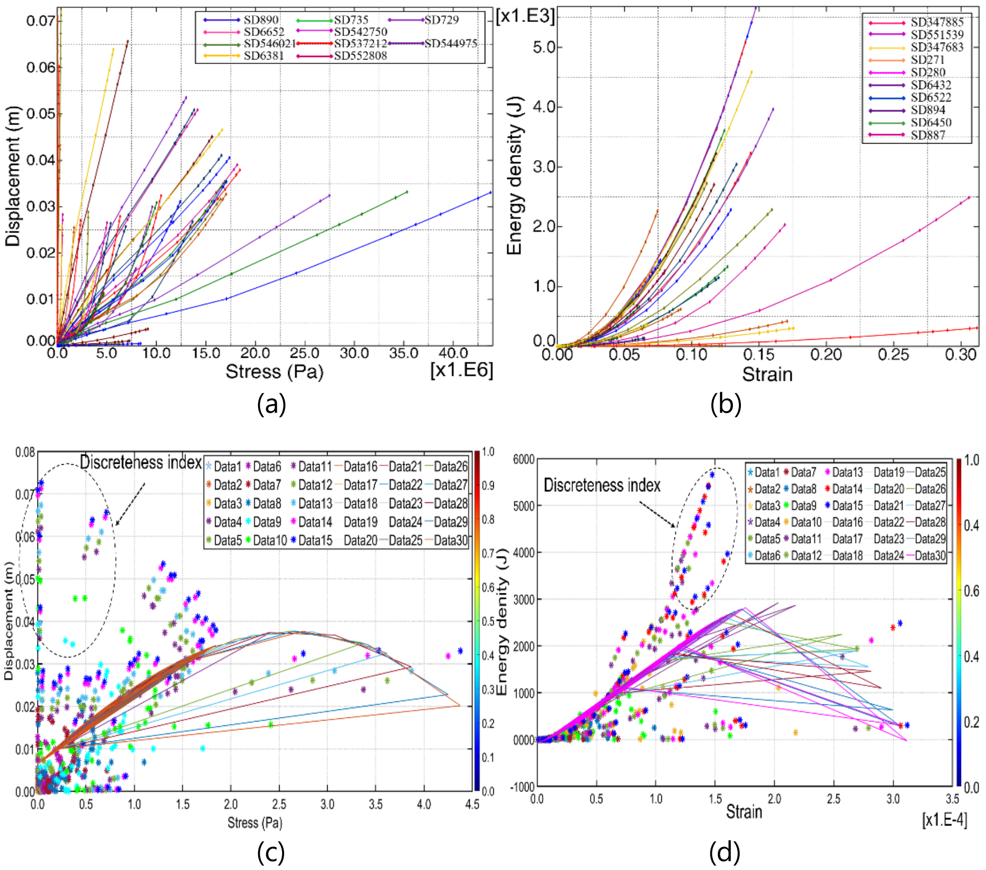


Figure 5.13. Number analysis of 33#. (a) stress and displacement. (b) stain and energy density. (c) finite analysis of stress and displacement. (d) finite analysis of strain and energy density.

Sources: Own elaboration, and anaiysis used the Abaqus software.

Monitoring point location: 347885 element → Located at a position of the second cross beam of the right line main tower; 551539 element → Located at a position of the main tower between the first and second cross beams of the right line main tower; 347683 element → Located at a position of the second cross beam of the right line main tower; 271 element → Located at contact surface between left line main tower and girder; 280 element → Located at contact surface between right line main tower and girder) (Figure 5.13-b).

The energy density ranking are: 5,655.27J (6432 element) ⟶ 5,398.21J (6522 element) → 3,963.36J (894 element) → 3,606.27J (6450 element) → 3,228.37J (887 element).

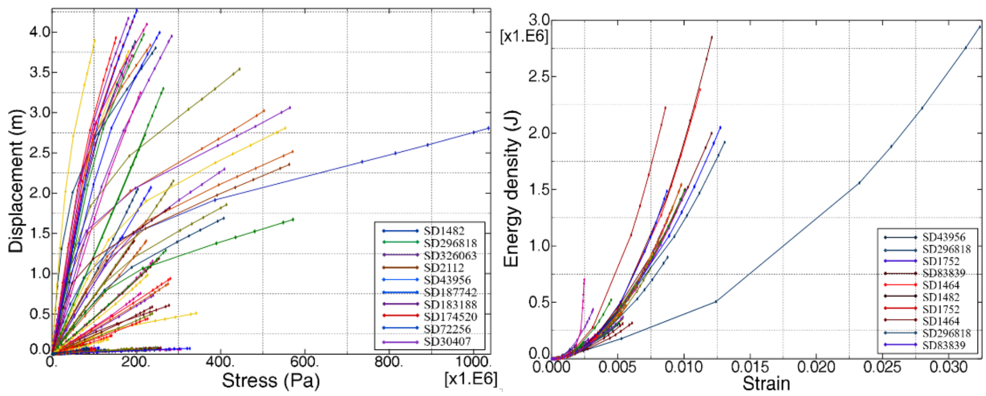
The strain number are: 0.000,147 (6432 element) ↔ 0.000,144 (6522 element) ↔ 0.000,160 (894 element) ↔ 0.000,124 (6450 element) ↔ 0.000,144 (887 element).

Monitoring point location: 6432 element → Located at 1/3H above the contact surface between the right line main tower and girder; 6522 element → Located at 1/3H above the contact surface between the left line main tower and girder; 894 element → Located at upper position of the first cross beam of the main tower; 6450 element → Located at position of girder between the first and second cross beams of the right line; 887 element → Located at position of the first cross beam of the left line main tower) (Figure 5.13-b).

Figures 5.13-c and d are the fitting analysis curves of stress-displacement and strain-energy density, judging from the synthesis of linear sequence and degree of freedom. A small number of discrete elements in 33#, accounting for 10% of the total monitoring data, indicating that the boundary conditions of each group of constraints are controlled by stress and energy are continuous and effective after optimization.

Judgment conclusion: Through the comprehensive evaluation in Figure 5.13, there is no redundant structure in 33#, and it does not meet the conditions of TO. The structural optimization is completed in the design stage.

Stay cable: The deformation and vibration of stay cables under static and dynamic loads are the leading indicators to determine the stability of bridges and a compassionate nonlinear equilibrium system analysis (Figure 5.14). 84 groups of stress and displacement are analyzed.



(a) (b)

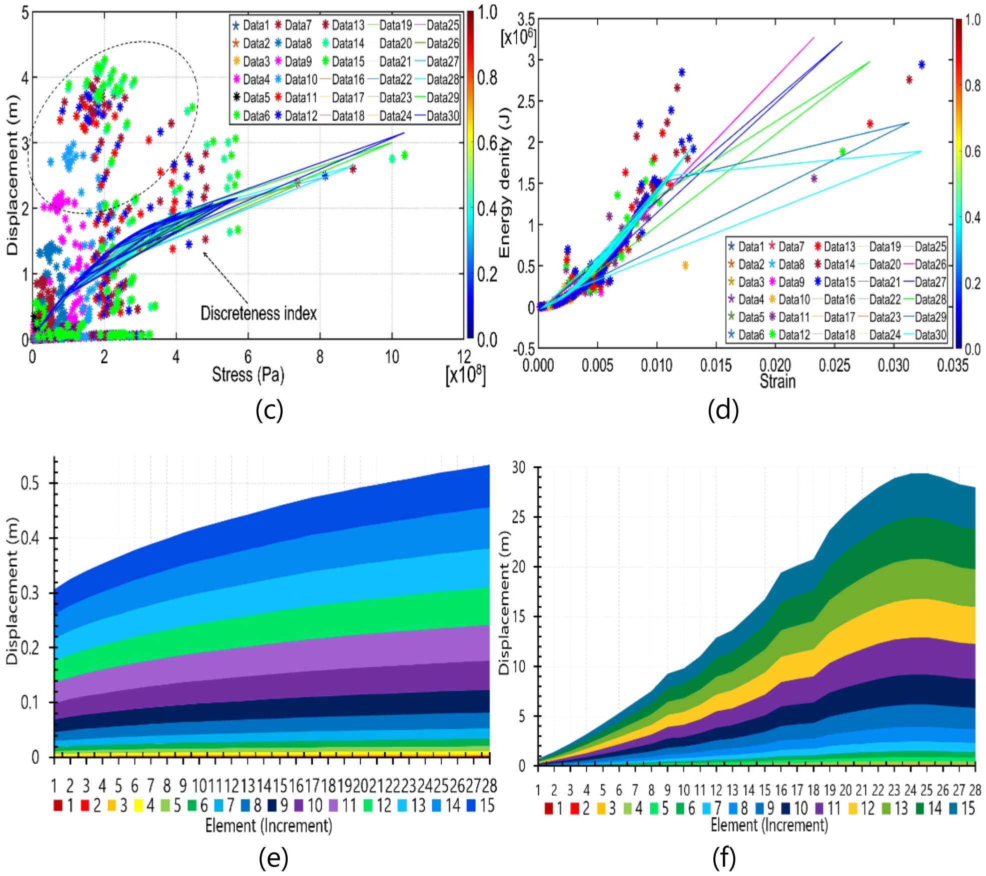


Figure 5.14. Number analysis of stay cable#. (a) stress and displacement. (b) stain and energy density. (c) finite analysis of stress anddisplacement. (d) finite analysis of strain and energy density. (e) Y-direction displacement analysis of stay cables. (f) X-direction displacement analysis of stay cables.

Sources: Own elaboration, and anaiysis used the Abaqus software.

The stress ranking are: 1,035,198,848Pa (1482 element) → 571,207,168Pa (296818 element) → 1,570,634,368Pa (326063 element) → 564,616,768Pa (2112 element) → 553,493,568Pa (43956 element).

The displacement number are: 2.81m (1482 element) ↔ 1.67m (296818 element) ↔ 2.52m (326063 element) ↔ 3.06m (2112 element) ↔ 2.81m (43956 element).

Monitoring point location: 1482 element → Located at contact surface between the 17th cable on the left side of the left line and the top surface of the girder; 296818 element → Located at the contact surface between the 11th cable on the right side of the right line and the top surface of the girder; 326063 element → Located at contact surface between the 15th cable on the right side of the right line and the top surface of the girder; 2112 element → Located at contact surface between the 18th cable on the right side of the right line and the top surface of the girder; 43956 element → Located at contact surface between the 17th cable on the right side of the left line and the top surface of the girder) (Figure 5.14-a).

The displacement number are: 4.271m (187742 element) ↔ 4.171m (183188 element) ↔ 4.127m (174520 element) ↔ 3.994m (72256 element) ↔ 3.972m (30407 element).

The stress ranking are: 201,018,816Pa (187742 element) ↔ 181,009,920 Pa (183188 element) ↔ 190,607,392Pa (174520 element) ↔ 254,940,416Pa (72256 element) ↔ 218,000,672 Pa (30407 element).

Monitoring point location: 187742 element → Located at contact between the 25th cable on the right side of the left line and the top surface of the girder; 183188 element → Located at contact surface between the 27th cable on the right side of the left line and the top surface of the girder; 174520 element → Located at contact surface between the 28th cable on the right side of the left line and the top surface of the girder; 72256 element → Located at contact surface between the 24th cable on the right side of the right line and the top surface of the girder; 30407 element → Located at contact surface between the 25th cable on the right side of the left line and the top surface of the girder) (Figure 5.14-a).

The strain ranking are: 0.013,1 (43956 element) → 0.012,7(296818 element) → 0.012,1 (1752 element) → 0.012,08 (83839 element) → 0.011,2 (1464 element).

The energy density ranking are: 1,919,511.75J (43956 element) → 2,048,088.5J (296818 element) → 2,847,882.25J (1752 element) → 1,997,570.5J (83839 element) → 2,385,289J (1464 element).

Monitoring point location: 43956 element → Located at contact surface between the 17th cable on the left side of the right line and the top surface of the girder; 296918 element → Located at contact surface between the 11th cable on the right side of the right line and the top surface of the girder; 1752 element → Located at contact surface between the 17th cable on the right side of the right line and the top surface of the girder; 83839 element → Located at contact surface between the 14th cable on the left side of the right line and the top surface of the girder; 1464 element → Located at contact surface between the 19^{th} cable on the left side of the left line and the top surface of the girder) (Figure 5.14-b).

The energy density ranking are: 2,941,172.5J (1482 element) → 2,847,882.25J (1752 element) → 2,385,289J (1464 element).

The strain ranking are: 0.032,4 (1482 element) → 0.012,1 (1752 element) → 0.011,2 (1464 element).

Monitoring point location: 1482 element → Located at contact surface between the 17th cable on the left side of the left line and the top surface of the girder; 1752 element → Located at contact surface between the 17th cable on the left line and the top surface of the girder; 1464 element → Located at contact surface between the 15th cable on the left side of the right line and the top surface of the girder) (Figure 5.14-b).

In order to analyze the displacement state of the stay cable, the contact direction between the main beam and the stay cable is specified as the x-axis direction. Moreover, the contact direction between the central tower and the stay cable is specified as the y-axis. The displacement of each joint of the x-axis and y-axis is detected, respectively.

The preciseness of scientific research is verified in Figures 5.14c and d. In the stress-displacement data fitting analysis, it is found that 24% of the elements are discretely distributed, and the stay cable has a redundant structure, so TO can be conducted. The strain-energy density fitting analysis found that the energy of the original size of the stay cable has been maximized under the load, and the homogenized configuration and layout have been completed inside the material. Figure 5.14-d shows that the stay cable does not have TO conditions.

Judgment conclusion: Through comprehensive analysis, within the load response range of stay cable, it is judged from stress-displacement that there is a redundant structure, and the energy in the system has a failure. Kinetic energy does not meet TO conditions, which needs further study. The conclusion is that the stay cable does not meet TO conditions and cannot be loaded twice.

Girder # (the research object is the finite element coupling analysis of box girder of CSB, and the approach bridge is studied in 4.3.2) is the key component of finite element analysis, and 62 elements are selected.

The stress ranking are: 537,947,456Pa (3768 element) → 467,543,072Pa (6359 element) → 364,803,264Pa (795 element) → 296,165,344Pa (462693 element) → 286,245,216Pa (338363 element).

The displacement number are: 0.252m (3768 element) ↔ 0.326m (6359 element) ↔ 0.377m (795 element) ↔ 4.497m (462693 element) ↔ 3.803m (338363 element).

Monitoring point location: 3768 element → Located at girder above left 32# pier of left line; 6359 element → Located at girder above right 34# pier of left line; 795 element → Located at girder above right 34# pier of left line; 462693 element → Located at contact between the right 27# steel strand of the right line and the girder; 338363 element → Located at girder 3m in front of the left 28# steel strand of right line) (Figure 5.15-a).

The displacement number are: 6.689m (338907 element) → 6.353m (338954 element) → 6.352m (476963 element) → 6.342m (509789 element) → 5.598m (339007 element).

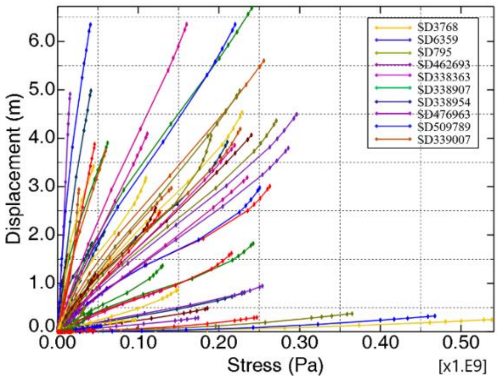
The stress ranking are: 220,286,256Pa (338907 element) → 181,009,920Pa (338954 element) → 159,904,688Pa (476963 element) → 40,472,472Pa (509789 element) → 255,371,712 Pa (339007 element).

Monitoring point location: 338907 element → Located at displacement of 2m at the contact surface between the 22nd cable on the left side of the left line and the girder; 338954 element → Located at displacement of 2m at the contact surface between the 19th cable on the left side of the left line and the girder; 476963 element → Located at displacement of 2m at the contact surface between the 26th cable on the right side of the left line and the girder; 509789 element → Located at contact surface between the 18th cable on the right side of the left bar and the top surface of the girder; 339007 element → Located at contact surface between the 14th cable on the right side of the left line and the top surface of the girder) (Figure 5.15-a).

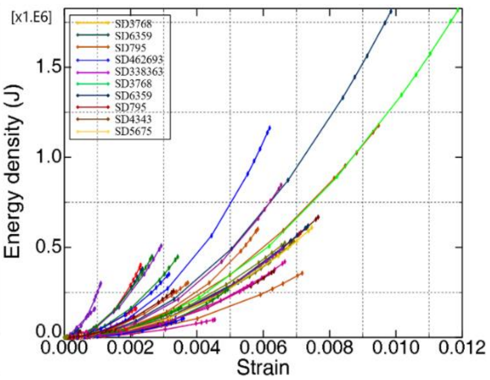
The strain ranking are: 0.011,9 (3768 element) → 0.010 (6359 element) → 0.010 (795 element) → 0.006 (462693element) → 0.006 (338363element).

The energy density ranking are: 1,816,879.875J (3768 element) → 1,809,853J (6359 element) → 1,177,259.625J (795 element) → 1,164,463.250J (462693 element) → 846,485.938J (338363 element).

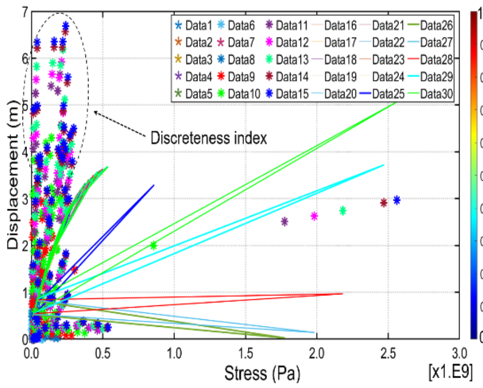
Monitoring point location: 3768 element → Located at girder above left 32# pier of left line; 6359 element → Located at girder above right 34# pier of left line; 795 element → Located at girder above right 34# pier of left line; 462693 element → Located at contact between the right 27# steel strand of the right line and the girder; 338363 element → Located at girder 3m in front of the left 28# steel strand of right line (Figure 5.15-b).


SD3768
SD6359
SD795
SD462693
SD338363
SD338907
SD338954
SD476963
SD509789
SD339007
Displacement (m)
Stress (Pa)
[x1.E9]

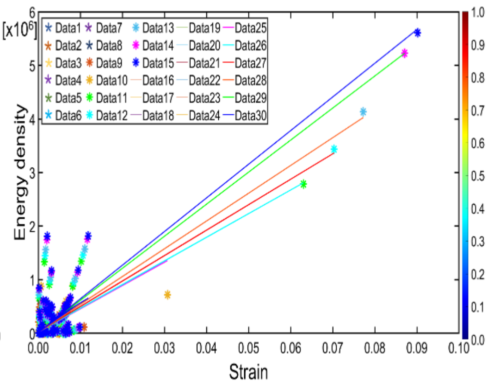
(a)


[x1.E6]
SD3768
SD6359
SD795
SD462693
SD338363
SD3768
SD6359
SD795
SD4343
SD5675
Energy density (J)
Strain

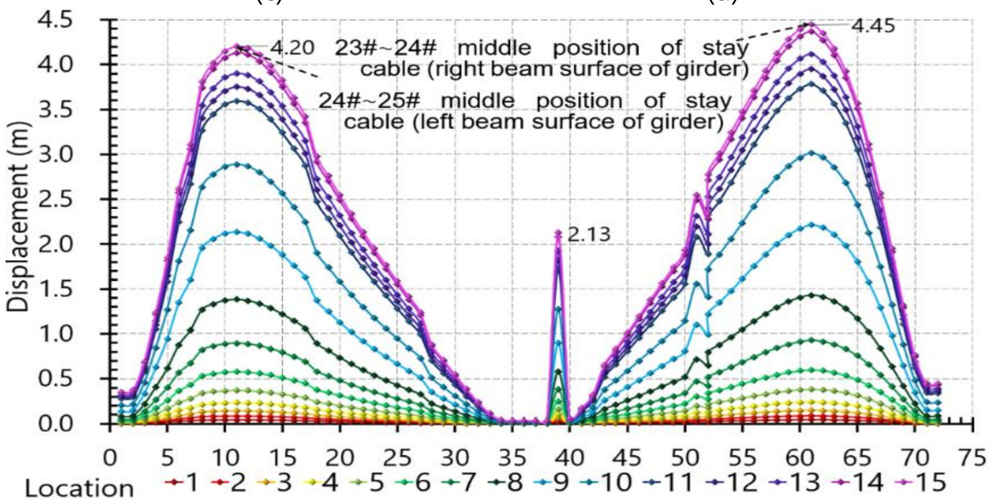
(b)


Discreteness index
Displacement (m)
Stress (Pa)
[x1.E9]

(c)


Energy density
Strain

(d)


4.20
4.45
2.13
23#~24# middle position of stay cable (right beam surface of girder)
24#~25# middle position of stay cable (left beam surface of girder)
Displacement (m)
Location

(e)

Figure 5.15. Number analysis of girder#. (a) stress and displacement. (b) stain and energy density. (c) finite analysis of stress anddisplacement. (d) finite analysis of strain and energy density. (e) displacement of girder.

Sources: Own elaboration, and anaiysis used the Abaqus software.

The stress distribution is discrete and concentrated in the middle. There are protruding measuring points locally, and the whole is evenly distributed.

According to Figure 5.15-c, the mathematical model fitting analysis is carried out for 62 groups of elements, showing that the displacement of the girder under dynamic load is apparent, and the strain is relatively concentrated, which is less than 0.5. The data discreteness accounts for 46% of the total, and there is the redundant structure of TO. In addition, the energy density analysis is conducted, and there is an abnormal response. Figure 5.15-d shows that the data are aggregated in a limited range, and the strain and energy consumption are constrained, indicating that the energy change in the structure of the girder during continuous loading is consumed and unloaded through the rapid displacement inside the whole bridge.

The energy density ranking are: 1,816,879.875J (3768 element) → 1,809,853J (6359 element) → 1,177,259.625J (795 element) → 668,179.063J (4243 element) → 609,241J (5675 element).

The strain ranking are: 0.011,9 (3768 element) ↔ 0.010 (6359 element) ↔ 0.010 (795 element) ↔ 0.008 (4343element) ↔ 0.008 (5675element).

Monitoring point location: 3768 element → Located at girder above right 34# pier of left line; 6359 element → Located at girder above right 34# pier of left line; 795 element → Located at girder above right 34# pier of left line; 4343 element → Located at contact surface between the 16th cable on the left side of the left line and the top surface of the girder; 5675 element → Located at 1m inside the contact surface between the 6th cable on the right side of the right line and the top surface of the girder) (Figure 5.15-b).

Figure 5.15-e shows the displacement of the girder. A total of 75 groups of elements are detected longitudinally, and one group is monitored every 6m. showing that the maximum displacement is in the middle of the 24#-25# stay cable of the 32#-33# girder, and the maximum displacement of the left girder is 4.20m. The maximum displacement of the right girder is in the middle of the 24#-25# stay cable, which is 4.448m. The displacement of the girder is a quadratic parabola mathematical model. Judgement conclusion: comprehensive analysis shows that girder has a large displacement under the continuous action

of dynamic load. However, the stress, strain, and energy show finite values, and the discreteness after data fitting disappears. A robust structure is formed inside after multiple energy consumption, and there is no redundant structure, and it does not meet TO conditions.

The structure of 34# pier is relatively simple, and the stress data obtained from 20 groups of monitoring points are 480,609,536Pa (236 element) → 464,790,400Pa (247 element) → 370,224,064Pa (244 element) → 332,144,064Pa (244 element) → 332,144,064Pa (246 element) → 302,114,560Pa (237 element).

The displacement number are: 0.322m (236 element) ↔ 0.342m (247 element) ↔ 0.323m (244 element) ↔ 0.325m (246 element) ↔ 0.332m (237 element).

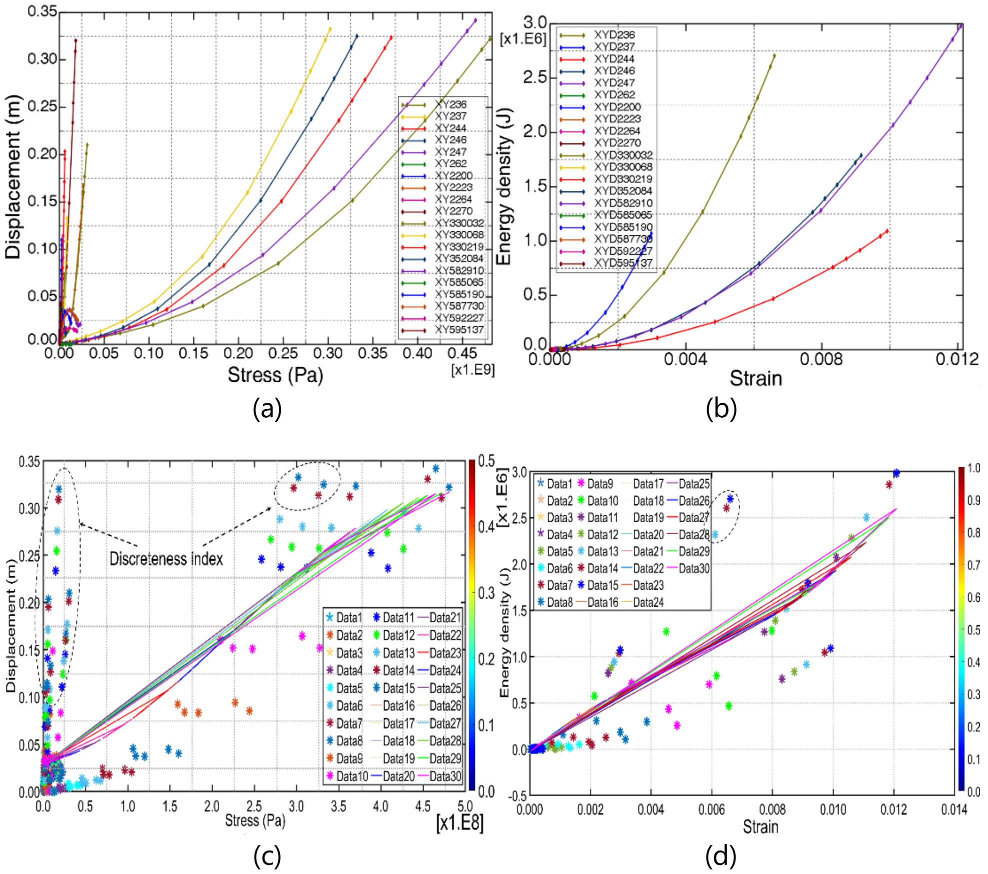


Figure 5.16. Number analysis of 34#. (a) stress and displacement. (b) stain and energy density. (c) finite analysis of stress anddisplacement. (d) finite analysis of strain and energy density.

Sources: Own elaboration, and anaiysis used the Abaqus software.

Monitoring point location: 236 element → Located at support above right 34# pier of left line; 247 element → Located at upport above right 34# pier of right line; 244 element → Located at cushion above right 34# pier of left line; 246 element → Located at cushion above right 34# pier of right line; 237 element → Located at support above right 34# pier of right line (Figure 5.16-a).

The displacement number are: 0.342m (247 element) ↔ 0.332m (237 element) ↔ 0.325m (246 element) ↔ 0.323m (244 element) ↔ 0.322m (236 element).

The stress ranking are: 464,790,400Pa (247 element) → 302,114,560Pa (237 element) → 332,144,064Pa (246 element) → 370,224,064Pa (236 element) → 480,609,536Pa Pa (236 element).

Monitoring point location: 247 element → Located at support above right 34# pier of right line; 237 element → Located at support above right 34# pier of right line; 246 element → Located at cushion above right 34# pier of right line; 244 element → Located at cushion above right 34# pier of left line; 236 element → Located at support above right 34# pier of left line (Figure 5.16-a).

The strain ranking are: 0.012,1 (247 element) ↔ 0.009,9 (244 element) ↔ 0.009,2 (246 element) ↔ 0.006,6 (236 element) ↔ 0.003 (237 element).

The energy density ranking are: 2,979,908.50J (247 element) ↔ 1,091,015.50J (244 element) ↔ 1,792,460.75J (246 element) ↔ 2,704,823.75J (236 element) ↔ 1,070,038.50J (237 element).

Monitoring point location: 247 element → Located at support above right 34# pier of right line; 244 element → cushion above right 34# pier of left line; 246 element → Located at cushion above right 34# pier of right line; 236 element → Located at support above right 34# pier of left line; 237 element → Located at support above right 34# pier of right line) (Figure 5.16-b).

The energy density ranking are: 2,979,908.50J (247 element) → 2,704,823.75J (236 element) → 1,792,460.75J (246 element) → 1,091,015.50J (244 element) → 1,070,038.50J (237 element).

The strain ranking are: 0.012,1 (247 element) ↔ 0.006,6 (236 element) ↔ 0.009,2 (246 element) ↔ 0.009,9 (244 element) ↔ 0.003 (237 element).

Monitoring point location: 247 element → Located at support above right 34# pier of right line; 236 element → Located at support above right 34# pier of right line; 246 element → Located at cushion above right 34# pier of right line; 244 element → Located at cushion above right 34# pier of left line; 237 element → Located at support above right 34# pier of right line (Figure 5.16-b).

Figure 5.16-c shows the fitting analysis of monitoring points. There are two discrete areas. Elements account for 27% with a low ratio, so it is difficult to determine the existence of redundant structure. Figure 5.16-d shows the strain-energy data fitting, indicating no redundant system, and the energy transfer is the same as Figure 5.12-d. Under the action of dynamic load, the strain energy inside the structure is quickly dissipated to the foundation and released.

Judgement conclusion: comprehensive analysis shows no redundant structure in 34#, so TO research and analysis cannot be continued.

JMB is completed according to finite element theoretical model analysis in 4.1, laying a foundation for TO under specific constraints, establishing a theoretical mathematical model, and Eqs. 4.5~4.10 in 4.1~4.2. A total of 15 groups are selected from 32#, 33#, stay cable, girder, and 34# test data, respectively, and 75 groups of data are used to analyze JMB sensitivity (Table 5.7).

Table 5.7. Parameter analysis of JMB

Structure	**32#**			
Parameter	**Stress (10^6, Pa)**	**Displacement (m)**	**Strain**	**Energy (J)**
1	2,640.00	0.253,000	0.007,120	1,490,000.0
2	4,430.00	0.272,000	0.013,100	2,810,000.0
3	3,920.00	0.252,000	0.010,700	1,450,000.0
4	3,350.00	0.261,000	0.003,890	1,320,000.0
5	4,680.00	0.249,000	0.007,090	2,340,000.0
6	643.00	0.085,400	0.000,141	23,400.00
7	825.00	0.053,600	0.002,390	57,400.00
8	175.00	0.249,000	0.000,200	5,590.00
9	473.00	0.245,000	0.000,409	28,800.00
10	141.00	0.051,400	0.000,375	2,850.00
11	278.00	0.072,300	0.0004,26	13,400.00
12	296.00	0.119,000	0.000,221	15,100.00
13	179.00	0.184,000	0.000,979	4,970.00

14	172.00	0.067,700	0.000,138	4,500.00
15	155.00	0.029,200	0.000,530	3,830.00
Structure	**33#**			
Parameter	**Stress (10^6, Pa)**	**Displacement (m)**	**Strain**	**Energy (J)**
16	275.00	0.045,100	0.000,310	5,660.00
17	353.00	0.063,900	0.000,310	5,400.00
18	438.00	0.037,900	0.000,180	3,960.00
19	156.00	0.041,000	0.000,170	3,610.00
20	165.00	0.040,600	0.000,170	3,230.00
21	185.00	0.043,300	0.000,237	3,430.00
22	166.00	0.050,900	0.000,087	1,850.00
23	174.00	0.071,000	0.000,080	1,230.00
24	142.00	0.039,000	0.001,940	110,000.00
25	182.00	0.065,700	0.000,364	20,500.00
26	166.00	0.072,600	0.000,293	4,440.00
27	138.00	0.060,200	0.000,122	3,910.00
28	169.00	0.050,900	0.000,127	4,000.00
29	171.00	0.053,500	0.000,140	1,290.00
30	171.00	0.046,500	0.000,141	4,760.00
Structure	**Stay cable**			
Parameter	**Stress (10^6, Pa)**	**Displacement (m)**	**Strain**	**Energy (J)**
31	10,400.00	4.270,000	0.013,100	2,940,000.00
32	5,710.00	4.170,000	0.012,700	2,850,000.00

33	15,700.00	4.130,000	0.012,100	2,390,000.00
34	5,650.00	3.990,000	0.012,100	2,050,000.00
35	5,530.00	3.970,000	0.011,200	2,000,000.00
36	2,510.00	1.800,000	0.007,760	973,000.00
37	2,750.00	3.900,000	0.008,500	1,170,000.00
38	2,690.00	1.440,000	0.008,310	1,120,000.00
39	2,770.00	1.850,000	0.008,570	1,190,000.00
40	2,870.00	3.700,000	0.008,880	1,270,000.00
41	2,600.00	2.790,000	0.008,040	1,040,000.00
42	2,900.00	2.140,000	0.008,980	1,300,000.00
43	2,850.00	3.260,000	0.008,820	1,260,000.00
44	2,590.00	1.590,000	0.008,030	1,040,000.00
45	2,550.00	1.430,000	0.007,880	1,000,000.00
Structure	**Girder**			
Parameter	**Stress (10^6, Pa)**	**Displacement (m)**	**Strain**	**Energy (J)**
46	5,380.00	4.180,000	0.009,480	525,000.00
47	4,680.00	4.530,000	0.011,900	1,180,000.00
48	3,650.00	4.370,000	0.007,660	1,820,000.00
49	2,960.00	4.500,000	0.007,140	668,000.00
50	2,860.00	4.980,000	0.007,350	582,000.00
51	2,470.00	5.600,000	0.009,850	620,000.00
52	2,630.00	6.350,000	0.007,470	602,000.00
53	2,420.00	6.690,000	0.006,920	1,810,000.00

54	2,510.00	6.350,000	0.006,320	609,000.00
55	2,710.00	4.980,000	0.006,650	532,000.00
56	2,400.00	4.980,000	0.006,560	4,920,00.00
57	25,600.00	4.920,000	0.006,540	846,000.00
58	2,540.00	40,500,000.00	0.007,170	509,000.00
59	2,410.00	6.340,000	0.006,190	1,160,000.00
60	2,550.00	4.100,000	0.090,200	5,610,000.00
Structure	**34#**			
Parameter	**Stress (10^6, Pa)**	**Displacement (m)**	**Strain**	**Energy (J)**
61	4,810.00	0.342,000	0.006,610	2,700,000.00
62	4,650.00	0.325,000	0.002,990	1,070,000.00
63	3,700.00	0.323,000	0.009,920	1,090,000.00
64	3,320.00	0.332,000	0.009,160	1,790,000.00
65	3,020.00	0.322,000	0.012,100	2,980,000.00
66	267.00	0.073,700	0.000,154	9,280.00
67	183.00	0.110,000	0.000,241	3,290.00
68	309.00	0.168,000	0.000,434	10,200.00
69	86.00	0.114,000	0.000,320	715.00
70	76.90	0.320,000	0.000,190	826.00
71	233.00	0.210,000	0.000,181	8,420.00
72	136.00	0.133,000	0.000,238	3,110.00
73	132.00	0.203,000	0.000,180	2,670.00
74	209.00	0.025,000	0.000,163	6,750.00
75	200.00	0.023,700	0.000,154	6,180.00

Sources: Own elaboration, and use the abaqus software analysis.

According to Eq 4.10 and Table 5.10, model parameters are determined:

$$[R]^k = \begin{bmatrix} 2.64\times10^{8} & 4.43\times10^{8} & \cdots & \cdots & 1.79\times10^{7} & 1.72\times10^{7} & 1.55\times10^{7} \\ 2.75\times10^{7} & 3.53\times10^{7} & \cdots & \cdots & 1.69\times10^{7} & 1.71\times10^{7} & 1.71\times10^{7} \\ 1.04\times10^{9} & 5.71\times10^{8} & \cdots & \cdots & 2.85\times10^{8} & 2.59\times10^{7} & 2.55\times10^{8} \\ 5.38\times10^{8} & 4.68\times10^{8} & \cdots & \cdots & 2.54\times10^{8} & 2.41\times10^{8} & 2.55\times10^{8} \\ 4.81\times10^{8} & 4.65\times10^{8} & \cdots & \cdots & 1.32\times10^{7} & 2.09\times10^{7} & 2.00\times10^{7} \end{bmatrix}$$

$$[D]^k = \begin{bmatrix} 2.53\times10^{-1} & 2.72\times10^{-1} & \cdots & \cdots & 1.84\times10^{-1} & 6.77\times10^{-2} & 2.92\times10^{-2} \\ 4.51\times10^{-2} & 6.39\times10^{-2} & \cdots & \cdots & 5.09\times10^{-2} & 5.35\times10^{-2} & 4.65\times10^{-2} \\ 4.27 & 4.17 & \cdots & \cdots & 3.26 & 1.59 & 1.43 \\ 4.18 & 4.53 & \cdots & \cdots & 4.05\times10^{7} & 6.34 & 4.10 \\ 3.42\times10^{-1} & 3.25\times10^{-1} & \cdots & \cdots & 2.03\times10^{-1} & 2.50\times10^{-2} & 2.37\times10^{-2} \end{bmatrix}$$

$$[G]^k = \begin{bmatrix} 7.12\times10^{-3} & 1.31\times10^{-2} & \cdots & \cdots & 9.79\times10^{-4} & 1.\times10^{-4} & 5.30\times10^{-4} \\ 3.10\times10^{-4} & 3.10\times10^{-4} & \cdots & \cdots & 1.27\times10^{-4} & 1.40\times10^{-4} & 1.41\times10^{-4} \\ 1.31\times10^{-2} & 1.27\times10^{-2} & \cdots & \cdots & 8.82\times10^{-3} & 8.03\times10^{-3} & 7.88\times10^{-3} \\ 9.48\times10^{-3} & 1.19\times10^{-2} & \cdots & \cdots & 7.17\times10^{-3} & 6.19\times10^{-3} & 9.02\times10^{-2} \\ 6.61\times10^{-3} & 2.99\times10^{-3} & \cdots & \cdots & 1.80\times10^{-4} & 1.63\times10^{-4} & 1.54\times10^{-4} \end{bmatrix}$$

$$[E]^k = \begin{bmatrix} 1.49\times10^{6} & 2.81\times10^{6} & \cdots & \cdots & 4.97\times10^{3} & 4.50\times10^{3} & 3.83\times10^{3} \\ 5.66\times10^{3} & 5.40\times10^{3} & \cdots & \cdots & 4.00\times10^{3} & 1.29\times10^{3} & 4.76\times10^{3} \\ 2.94\times10^{6} & 2.85\times10^{6} & \cdots & \cdots & 1.26\times10^{6} & 1.04\times10^{6} & 1.00\times10^{6} \\ 5.25\times10^{5} & 1.18\times10^{6} & \cdots & \cdots & 5.09\times10^{5} & 1.16\times10^{6} & 5.61\times10^{6} \\ 2.70\times10^{6} & 1.07\times10^{6} & \cdots & \cdots & 2.67\times10^{3} & 6.75\times10^{3} & 6.18\times10^{3} \end{bmatrix}$$

$$\frac{\sigma w_n}{\sigma s_n} = \begin{bmatrix} 0.00 \\ 1.00\times10^{-2} \\ 2.00\times10^{-2} \\ 3.50\times10^{-2} \\ 5.75\times10^{-2} \\ 9.13\times10^{-2} \\ 1.42\times10^{-1} \\ 2.18\times10^{-1} \\ 3.32\times10^{-1} \\ 5.03\times10^{-1} \\ 6.73\times10^{-1} \\ 8.44\times10^{-1} \\ 8.83\times10^{-1} \\ 9.22\times10^{-1} \\ 9.81\times10^{-1} \\ 1.00 \end{bmatrix}$$

$$\{\triangle\sigma\}_k^v = \begin{bmatrix} 2.17\times10^{4} & 0 & \cdots & \cdots & 0 & 0 & 0 \\ 3.41\times10^{12} & 0 & \cdots & \cdots & 0 & 0 & 0 \\ 3.93\times10^{11} & 0 & \cdots & \cdots & 0 & 0 & 0 \\ 1.69\times10^{11} & 0 & \cdots & \cdots & 0 & 0 & 0 \\ 0 & 0 & \cdots & \cdots & 0 & 0 & 0 \end{bmatrix}$$

Through calculation and analysis, it is determined that 32# finite element optimization constraint interval is:

Stress < 467,948,544Pa; Displacement < 0.271,857,977m; Strain < 0.013,107,781; Energy density < 2,808,464.75J; Determine 35,247 < Sensitivity < 3,407,023,580,834.59.

5.3.2.2. JMB (Auxiliary bridge)

JMB approach bridge has 49 spans in total, and the superstructure is all T-beams, with a total of 490. 12 T-beams are installed in each span. This thesis selected the most unfavorable two-span sections 28#-30# for finite element coupling analysis (the most extended pile foundation in the approach bridge is 65~72m). The finite element grid is divided into 0.6-1.2, with 61,386 groups of elements. There are 0 analysis errors and 61,386 groups of analysis warnings in the monitoring data, accounting for 2.15% of the total. In the finite element plot contours on deformed shape, it can be found that the stress is concentrated in the mid-span, and the maximum pressure is concentrated in 29# mid span (Figure 5.17).

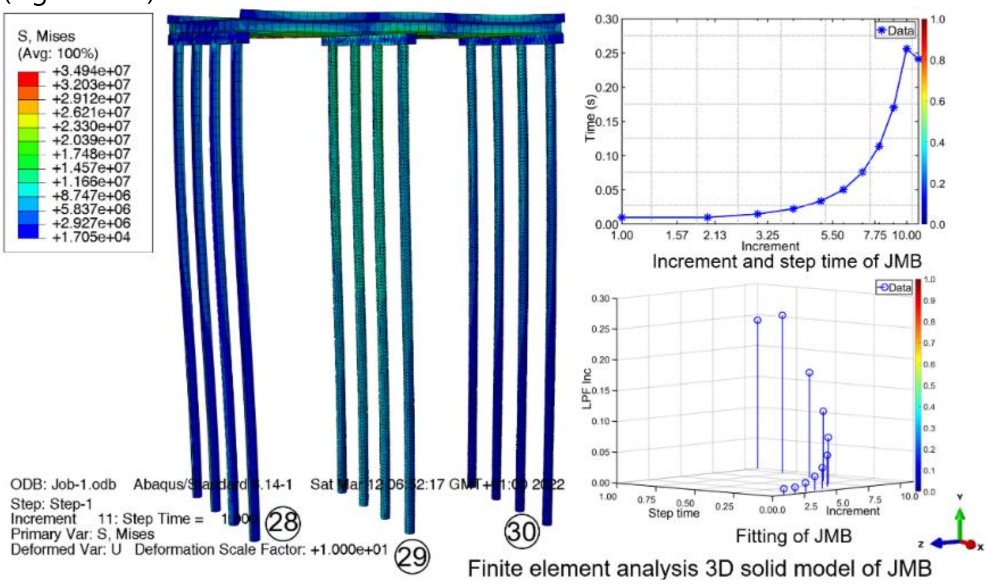


Figure 5.17. Finite model analysis of JMB (auxiliary bridge).

Sources: Own elaboration, and anaiysis used the Abaqus software.

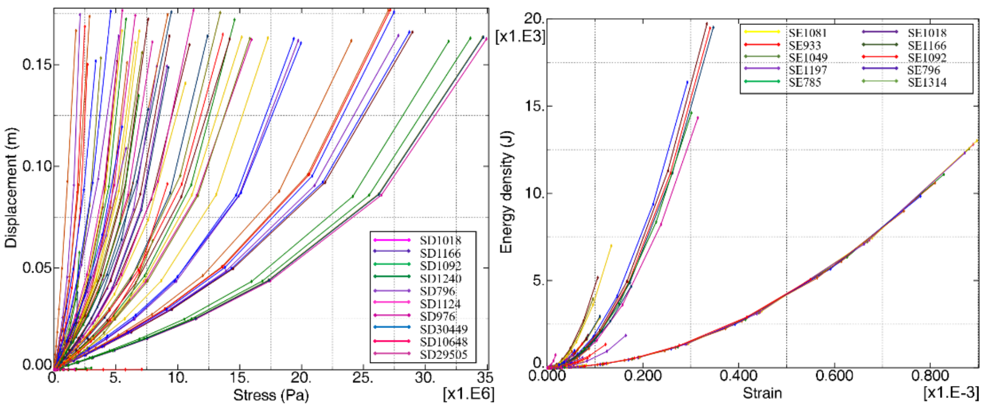
28#-30# is a T-beam structure of the same type, so their discreteness analysis can be conducted as a whole. 65 groups of data are monitored in the stress-displacement finite element iterative analysis, and the maximum stress element was 1018.

The stress ranking are: 34,938,088Pa (1018 element) → 34,665,824Pa (1166 element) → 34,633,764Pa (1092 element) → 3,362,7812Pa (1240 element) → 27,008,544Pa (796 element) → 11,274,018Pa (30449 element) → 5,526,377Pa (10648 element) → 4,585,019Pa (29505 element).

The displacement number are: 0.163m (1018 element) ↔ 0.163m (1166 element) ↔ 0.163m (1240 element) ↔ 0.177m (796 element) ↔ 0.177m (30449 element) ↔ 0.177m(10648 element) ↔ 0.176m (29505 element).

Monitoring point location: 1018 element → Located at bottom of the seventh T-beam on the middle support of 29# pier head; 1166 element → Located at bottom of the fifth T-beam On the middle support of 29# pier head; 1092 element → Located at bottom of the sixth T-beam on the middle support of 29# pier head; 1240 element → Located at bottom of the seventh T-beam on the middle support of 29#-30# pier head; 796 element → Located at bottom of the eighth T-beam of 28#-29# pier head; 30449 element → Located at bottom of 28# pier head; 10648 element → Located at bottom of 28# pier head; 29505 element → Located at bottom of 28# pier head) (Figure 5.18-a).

Through the numerical simulation analysis of 28 # - 30 # upper and lower structures, the rationality of the research method can be proved through model tests and numerical calculations. The finite element calculation results show that the model first appears to bend stress in the shear bending zone and then later extends a typical full-section stress transfer form laterally. The strain research process is consistent with the test. The shapes of several load-displacement curves obtained by finite element calculation are similar. The test's ultimate



(a) (b)

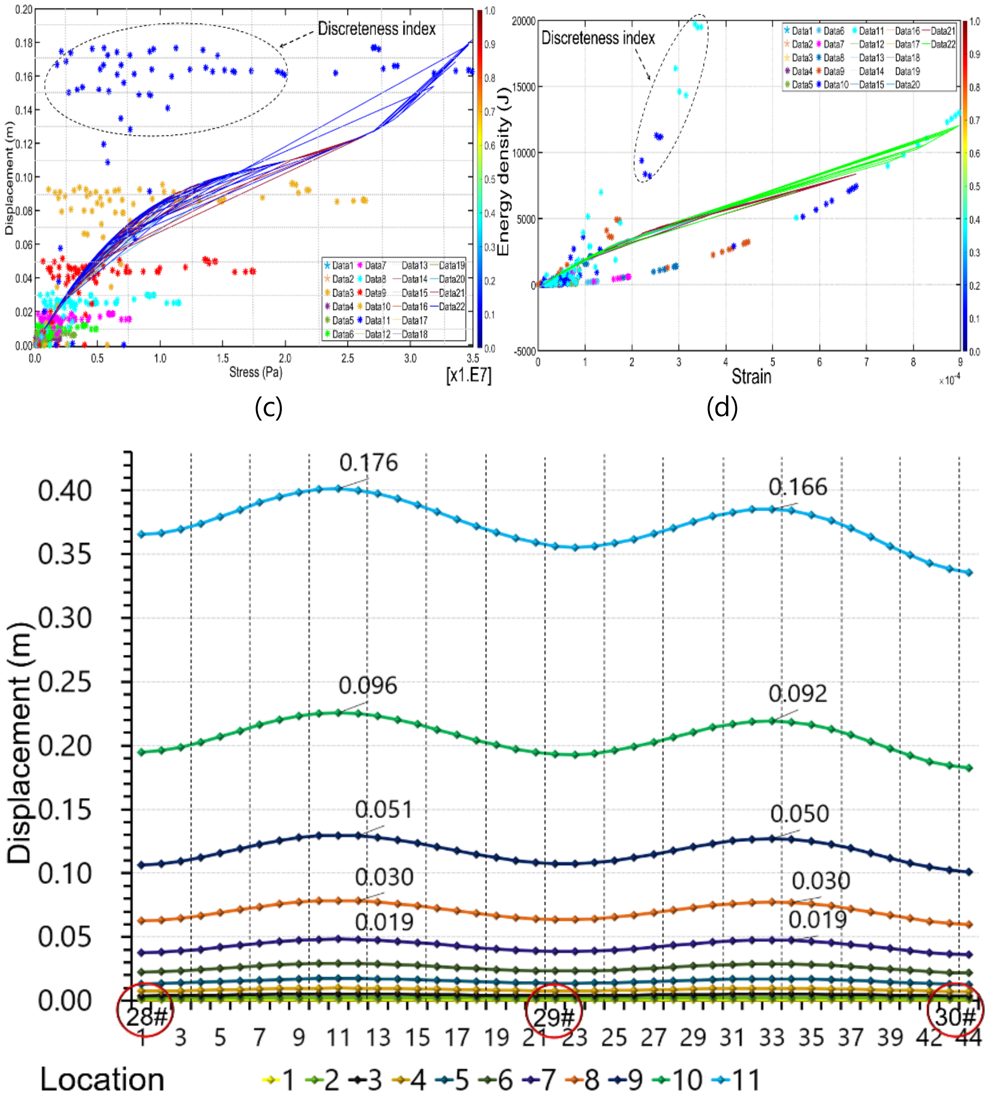


Figure 5.18. Number analysis of 28#~30#. (a) stress and displacement. (b) stain and energy density. (c) finite analysis of stress and displacement. (d) finite analysis of strain and energy density. (e) displacement of 28#~30# girder.

Sources: Own elaboration, and anaiysis used the Abaqus software.

strength value is consistent with the ultimate strength value calculated by the overall formula of the model. The reason is related to the time variation of concrete material, including the time variation of strength (compression, tension, shear, bonding, Etc.), the time variation of elastic modulus, and the time variation of material stress-strain constitutive relationship. In addition, the creep effect and shrinkage effect of concrete develop rapidly from pouring and curing to use.

60 groups of elements are monitored in Strain data, and the ranking are 0.000,896,836 (1081 element) → 0.000,889 (933 element) → 0.000,881 (1049 element) → 0.000,872 (1197 element) → 0.000,828(785 element).

Monitoring point location: 1081 element → Located at middle bottom plate of the sixth T-beam of 29#-30#; 933 element → Located at middle bottom plate of the sixth T-beam of 28#-29#; 1049 element → Located at middle bottom plate of the sixth T-beam of 28#-29#; 1197 element → Located at middle bottom plate of the fifth T-beam of 28#-29#; 785 element → Located at middle bottom plate of the tenth T-beam of 29#-30#) (Figure 5.18-b).

The energy ranking are 19,717.314,45J (1018 element) → 19,464.75J (1166 element) → 19,464.75J (1092 element) → 16,359.272,46J (796 element) → 14,590.997,07J (1314 element).

The strain ranking are: 0.000,334 (1018 element) ↔ 0.000,347 (1166 element) ↔ 0.000,340 (1092 element) ↔ 0.000,293 (796 element) ↔ 0.000,301 (1314 element).

The energy ranking are 19,717.314,45J (1018 element) → 19,464.75J (1166 element) → 19,464.75J (1092 element) → 16,359.272,46J (796 element) → 14,590.997,07J (1314 element).

The strain ranking are: 0.000,334 (1018 element) ↔ 0.000,347 (1166 element) ↔ 0.000,340 (1092 element) ↔ 0.000,293 (796 element) ↔ 0.000,301 (1314 element).

Monitoring point location: 1081 element → Located at bottom of the seventh T-beam on the middle support of 29# pier head; 1166 element → Located at bottom of the fifth T-beam on the middle support of 29# pier head; 1092 element → Located at bottom of the sixth T-beam on the middle support of 29# pier head; 796 element → Located at bottom of the tenth T-beam on the middle support of 29# pier head; 1314 element → Located at bottom of the third T-beam on the middle support of 29# pier head) (Figure 5.18-b).

Figure 5.18-c shows the fitting of the stress and displacement model, showing a redundant structure of elements, and it can meet TO conditions. Through the fitting of strain and energy density in Figure 5.18-d, it is judged that there is a small amount of redundant structure (accounting for 20% of the total).

Under load, the displacement of T-beam is less than that of box girder of CSB, and the maximum displacement is concentrated in the middle of two span T-beam. This conclusion is consistent with that of the bending moment analysis (Figure 5.18-e).

Comprehensive evaluation: 28#-30# T-beams approach bridge section has a discrete structure, so TO research can be carried out. Due to the many materials, an approach bridge will be used for TO analysis.

The theoretical mathematical model of the JMB approach bridge is established according to Eqs.4.5~4.9, which is used as the data of TO analysis paradigm. A total of 12 groups are selected from 28#-30# test data, respectively, and 48 groups of data are chosen to analyze the sensitivity and constraint parameters of the JMB approach bridge.

Table 5.8. Parameters of JMB (auxiliary bridge)

Structure	**28#-30#**			
Parameter	**Stress (Pa)**	**Displacement (m)**	**Strain**	**Energy (J)**
1	34,900,000.00	0.177,000	0.000,897	19,700.00
2	34,700,000.00	0.177,000	0.000,890	19,500.00
3	34,600,000.00	0.177,000	0.000,881	19,500.00
4	33,600,000.00	0.177,000	0.000,872	16,400.00
5	31,900,000.00	0.176,000	0.000,828	14,600.00
6	28,900,000.00	0.176,000	0.000,810	14,300.00
7	28,700,000.00	0.176,000	0.000,780	13,000.00
8	27,800,000.00	0.176,000	0.000,745	12,800.00
9	27,500,000.00	0.175,000	0.000,550	12,600.00
10	27,200,000.00	0.175,000	0.000,347	12,300.00
11	27,000,000.00	0.174,000	0.000,340	11,100.00

Sources: Own elaboration.

According to Eq 4.10 and Table 5.8, model parameters are determined:

$[R]^k = [3.49 \times 10^7 \quad 3.47 \times 10^7 \quad ,\cdots, \quad 2.75 \times 10^7 \quad 2.72 \times 10^7 \quad 2.70 \times 10^7]$

$[D]^k = [1.77 \times 10^{-1} \quad 1.77 \times 10^{-1} \quad ,\cdots, \quad 1.75 \times 10^{-1} \quad 1.75 \times 10^{-1} \quad 1.74 \times 10^{-1}]$

$[G]^k = [8.97 \times 10^{-4} \quad 8.90 \times 10^{-4} \quad ,\cdots, \quad 5.50 \times 10^{-4} \quad 3.47 \times 10^{-4} \quad 3.40 \times 10^{-4}]$

$[E]^k = [1.97 \times 10^4 \quad 1.95 \times 10^4 \quad ,\cdots, \quad 1.26 \times 10^4 \quad 1.23 \times 10^4 \quad 1.11 \times 10^4]$

$$\frac{\sigma w_n}{\sigma s_n} = \begin{bmatrix} 0.00 \\ 1.00 \times 10^{-2} \\ 2.00 \times 10^{-2} \\ 3.50 \times 10^{-2} \\ 5.75 \times 10^{-2} \\ 9.12 \times 10^{-2} \\ 1.42 \times 10^{-1} \\ 2.18 \times 10^{-1} \\ 3.32 \times 10^{-1} \\ 5.03 \times 10^{-1} \\ 7.59 \times 10^{-1} \\ 1.00 \end{bmatrix}$$

$$\{\triangle\,\sigma\}_k^v = [1.09 \times 10^6 \quad 0 \quad , \cdots , \quad 0 \quad 0 \quad 0]$$

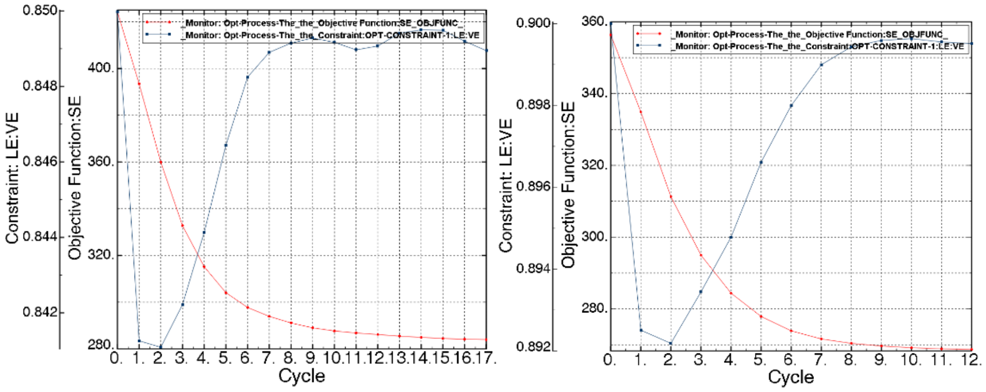
Through calculation and analysis, it is determined that 28#~30# finite element optimization constraint interval is: Stress < 34,938,088Pa; Displacement < 0.176,959,679m; Strain < 0.000,896,8; Energy density < 19,717.314J; Determine Sensitivity < 1,093,243.26.

5.3.3. Analysis of topology optimization

The analysis results in 5.3.2.1 and 5.3.2.2 show that only 32# and 28#-30# have TO conditions in the components of each part of the main bridge, which will be analyzed in this section.

5.3.3.1. Analysis of 32#

Under the original design load, 27,264 groups of elements in 32# are divided, of which analysis warning and analysis errors are all zero, and the grid division unit is 1.2. Eleven iterations occurred to complete the finite element analysis.



(a) (b)

Figure 5.19. TO analysis of 32#. (a) 85% value. (b) 90% value. (c) finite analysis of stress and displacement. (d) finite analysis of strain and energy density. (e) displacement of 28#~30# girder.

Sources: Own elaboration, and anaiysis used the Abaqus software.

The original volume of 32# was reduced by 15% (85% of the original book was reserved) for the first time, and 17 iterative cycles occurred. After the eighth cycle, the objective function data remained the same and fluctuated between 284 and 291. The constraint data had no significant change and fluctuated up and down at 0.849 (Figure 5.19-a).

The iterative compensation of the structure is the core principle of software optimization, and the intersection of the two lines is the balance point. After passing through the intersection, discrete branch lines appear, and the redundant parts of the structure are successively reduced until the internal stress reaches equilibrium.

After TO analysis, the mises stress range of the structure increased from 870.9~241,000 to 0.000,338~257,000. There was a significant increase in the small stress range and minimal values. The volume reduction of the system is mainly located in the middle of the pile cap and pier column. All the redundant structures around the pile cap have been reduced, but it was found that some pile foundations have been damaged outside the system, affecting the stability and safety of the main structure and pile foundation. The volume of the pier column near the middle of the pile cap was partially reduced, and an irregular strip-shaped cavity appeared (Figure 5.20-a). The structural effectiveness is difficult to be judged from the structural coupling after TO, but the detection data and sensitivity can consider.

Figure 5.20-b shows that the stress in the 32# structure tends to be stable and concentrated, and a small number of elements are dispersed in the surrounding area. Under the same load, the constraints in the structure have been concentrated. Figure 5.20-c shows the optimal analysis of the data, and a consistent conclusion is obtained. 24% of the elements are discretely distributed near the fitting interval, and all the others are within the appropriate interval.

$$[R]^k = \begin{bmatrix} 2.37\times10^5 & 2.28\times10^5 & 2.26\times10^5 & 2.24\times10^5 & 9.30\times10^4 \\ 7.37\times10^4 & 6.87\times10^4 & 6.86\times10^4 & 6.76\times10^4 & 6.17\times10^4 \end{bmatrix}$$

$$[D]^k = \begin{bmatrix} 1.77\times10^{-3} & 1.77\times10^{-3} & 1.76\times10^{-3} & 1.75\times10^{-3} & 1.74\times10^{-3} \\ 1.74\times10^{-3} & 1.73\times10^{-3} & 1.73\times10^{-3} & 1.73\times10^{-3} & 1.73\times10^{-3} \end{bmatrix}$$

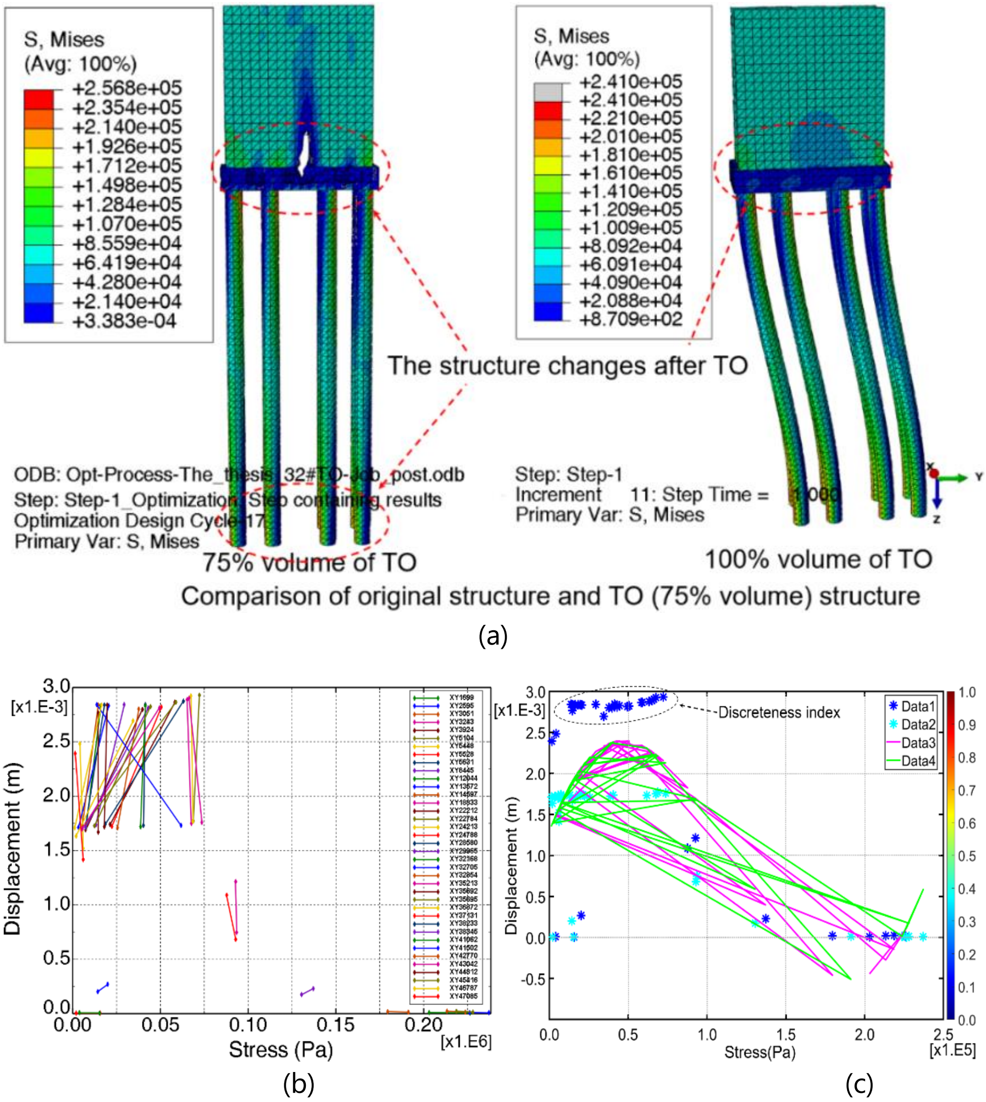


Figure 5.20. TO analysis of 32#. (a) 100% and 75% finite element coupling. (b) analysis of stress and displacement. (c) fitting analysis of stress and displacement.

Sources: Own elaboration, and anaiysis used the Abaqus software.

$\frac{\sigma w_n}{\sigma s_n} = \begin{bmatrix} 2.00 \\ 2.00 \end{bmatrix}$

Through Matlab program, we can obtain:

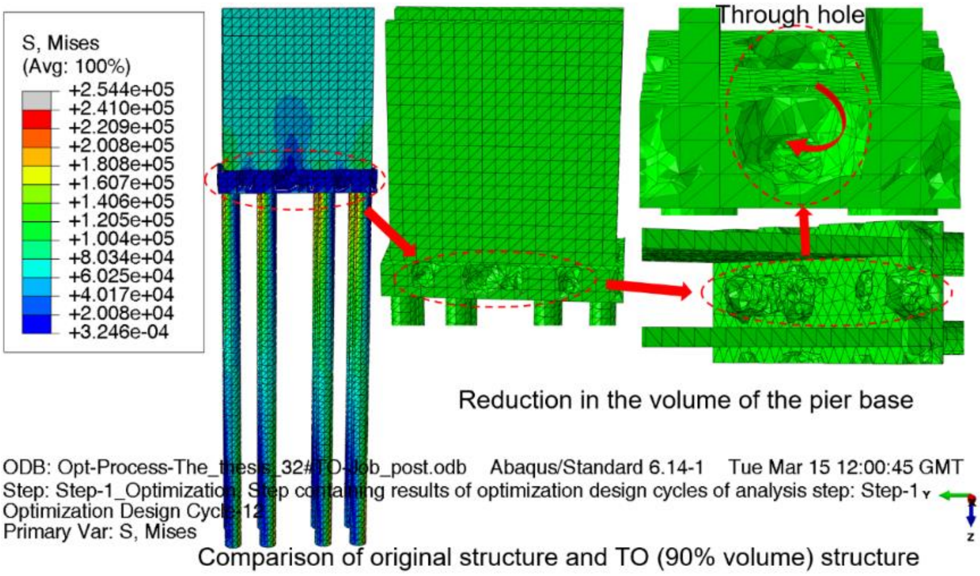
$$\{\triangle\,\sigma\}_k^v = \begin{bmatrix} 8.40\times10^2 & 8.06\times10^2 & 7.96\times10^2 & 7.83\times10^2 & 3.24\times10^2 \\ 2.56\times10^2 & 2.38\times10^2 & 2.38\times10^2 & 2.34\times10^2 & 2.14\times10^2 \end{bmatrix}$$

Table 5.9. TO data of 32#

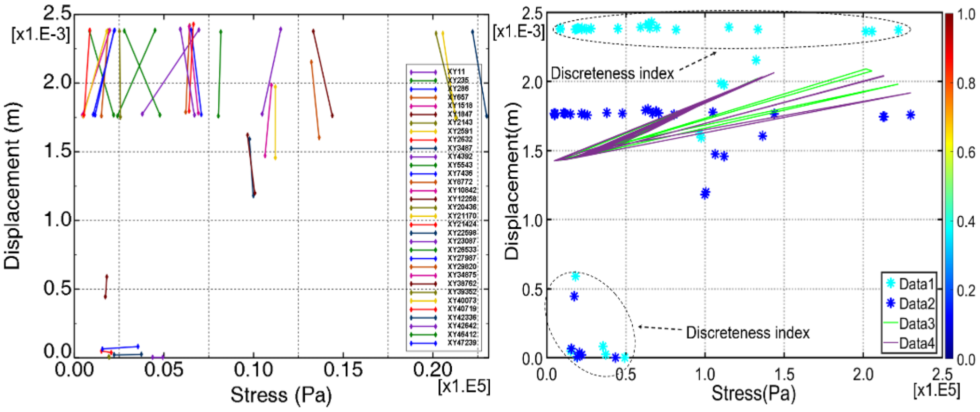
32#	Constrained interval data	85% TO	90% TO
Stress (Pa)	467,948,544	256,840	254,365
Displacement (m)	0.271,857,977	0.001,771,539	0.001,797,9
Strain	0.013,107,781	/	/
Energy density (J)	2,808,464.75	/	/
Sensitivity	21,741.35<S<3,407,023,580,834.59	213.61<S<840.18	352.83<S<827.00

Sources: Own elaboration.

The constraint interval is determined through the calculation and analysis when the volume of 32# is reduced by 15% after TO. Table 5.9 shows that all parameters meet the interval constraint values, 85% of the book TO optimization conclusion is valid, and the detected data have robustness. However, according to China's bridge structures' safety and design specifications, the reliability and attributes of pile foundation agreed in 4.2.2 have hidden dangers under load. Therefore, the conclusion is that TO does not meet the overall standard of constraints.



(a)



(b) (c)

Figure 5.21. TO analysis of 32#. (a) 90% finite element coupling. (b) analysis of stress and displacement. (c) fitting analysis of stress and displacement.

Sources: Own elaboration, and anaiysis used the Abaqus software.

The volume of 32# is reduced by 10% (90% of the original design) after secondary TO. A total of 12 iteration cycles are completed. Firstly, the optimization of various parts of the structure is checked, showing that the pile foundation is complete, and many materials in the middle of the pile cap are reduced, resulting in local structural penetration (Figure 5.19-b). Moreover, some redundant structures are reduced symmetrically on both sides of the pile cap. The pier column is complete and meets the specifications when checking the constraints according to the structural design requirements (Figure 5.21-a).

Figure 5.21-b shows the stress-displacement data analysis, showing that the structure's stress is still concentrated in a particular range. Compared with 85% of TO, it offers a broader discreteness and regionality. Figure 5.21-c shows the fitting data analysis, showing that the discreteness of the redundant internal structure is more prominent. The distribution area increases and the structure can be optimized again. From the three models in Figure 5.21, it can be seen that 32# meets the primary constraints in 90% of TO. Calculation and analysis of mathematical theoretical model:

$$[R]^k = \begin{bmatrix} 2.30\times10^5 & 2.13\times10^5 & 2.13\times10^5 & 1.44\times10^5 & 1.36\times10^5 \\ 1.12\times10^5 & 1.06\times10^5 & 1.05\times10^5 & 1.01\times10^5 & 9.97\times10^4 \end{bmatrix}$$

$$[D]^k = \begin{bmatrix} 1.08\times10^{-3} & 1.79\times10^{-3} & 1.78\times10^{-3} & 1.77\times10^{-3} & 1.77\times10^{-3} \\ 1.77\times10^{-3} & 1.77\times10^{-3} & 1.77\times10^{-3} & 1.77\times10^{-3} & 1.77\times10^{-3} \end{bmatrix}$$

$\frac{\sigma w_n}{\sigma s_n} = \begin{bmatrix} 2.00 \\ 2.00 \end{bmatrix}$

Through Matlab program, we can obtain:

$\{\triangle \sigma\}_k^v = \begin{bmatrix} 8.27 \times 10^2 & 7.63 \times 10^2 & 7.58 \times 10^2 & 5.09 \times 10^2 & 4.84 \times 10^2 \\ 3.97 \times 10^2 & 3.77 \times 10^2 & 3.72 \times 10^2 & 3.56 \times 10^2 & 3.53 \times 10^2 \end{bmatrix}$

Table 5.9 shows the final model judgment data, showing that in the sensitivity calculation, 90% of TO data are in line with the range of defined interval elements, so TO is successful this time.

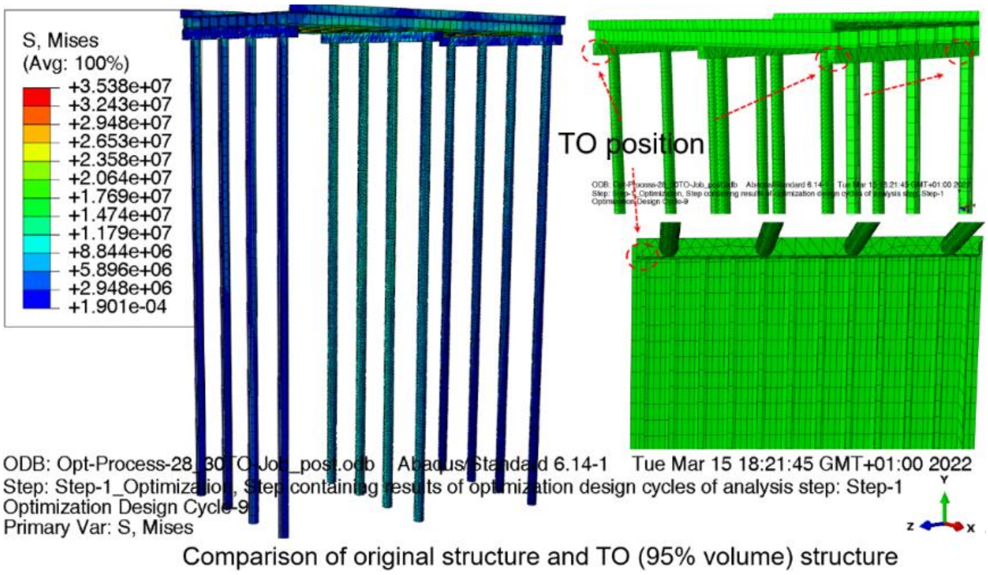
Final conclusion: 32# can minimize the volume of materials by 10%, and all indicators meet the standards of research and design specifications.

5.3.3.2. Analysis of 28#~30#

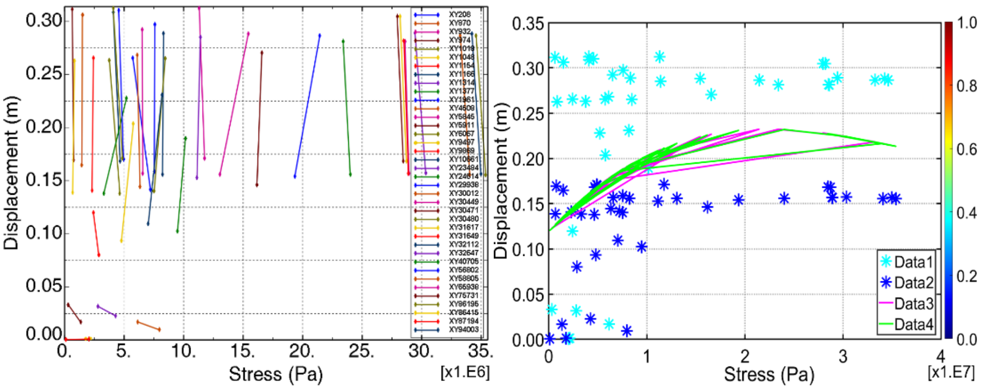
JMB approach bridge has a total of 45 spans. The two most unfavorable spans, 28#-30#, are analyzed in 5.3.2, concluding that they have a few redundant structures and meet TO conditions. In this section, we assume that 28#-30# can reduce the material consumption of a specific volume and apply this conclusion to other approach bridges because the multiple regression analysis of the maximum damage indicator of similar bridge structures under the same environmental conditions has been carried out. After the top indicator analysis, the conclusion can cover other component indicators (Goi & Kim, 2017); this theory also applies to this section.

At first, TO is set at 90%, and the structure is damaged after 13 design iteration cycles: there are defects in some pile foundation structures and T-beam, indicating TO is failed. Then, the reduction ratio was adjusted, and the volume parameter was set to 95%. After nine cycles, TO was completed, there was no defect in the pile foundation from the outside of the structure, and the T-beam was complete. TO was designed at the tie-beam end and in partial areas (Figure 5.22-a). Although the system meets the primary conditions of design specifications and optimization, it needs to be confirmed by the data analysis of the theoretical model.

Thirty-eight groups of elements were detected structurally, with a maximum stress of 1,018 points and stress = 35,375,944Pa, which increased by 4,054Pa compared with the stress data before optimization, and the minimum value compared with the stress data before optimization, and the minimum value interval increased. Figures 5.22-b and c show that the data discreteness is completely distributed in the gap, and there are many redundant materials in the structure. The conclusion of optimization analysis is consistent.



(a)



(b) (c)

Figure 5.22. TO analysis of 28#~30#. (a) 95% finite element coupling. (b) analysis of stress and displacement. (c) fitting analysis of stress and displacement.

Sources: Own elaboration, and anaiysis used the Abaqus software.

$$[R]^k = \begin{bmatrix} 3.54 \times 10^7 & 3.50 \times 10^7 & 3.03 \times 10^7 & 2.89 \times 10^7 & 2.89 \times 10^7 \\ 2.85 \times 10^7 & 2.87 \times 10^7 & 2.40 \times 10^7 & 1.93 \times 10^7 & 1.31 \times 10^7 \end{bmatrix}$$

$$[D]^k = \begin{bmatrix} 1.71 \times 10^{-1} & 1.71 \times 10^{-1} & 1.70 \times 10^{-1} & 1.69 \times 10^{-1} & 1.68 \times 10^{-1} \\ 1.68 \times 10^{-1} & 1.68 \times 10^{-1} & 1.65 \times 10^{-1} & 1.59 \times 10^{-1} & 1.56 \times 10^{-1} \end{bmatrix}$$

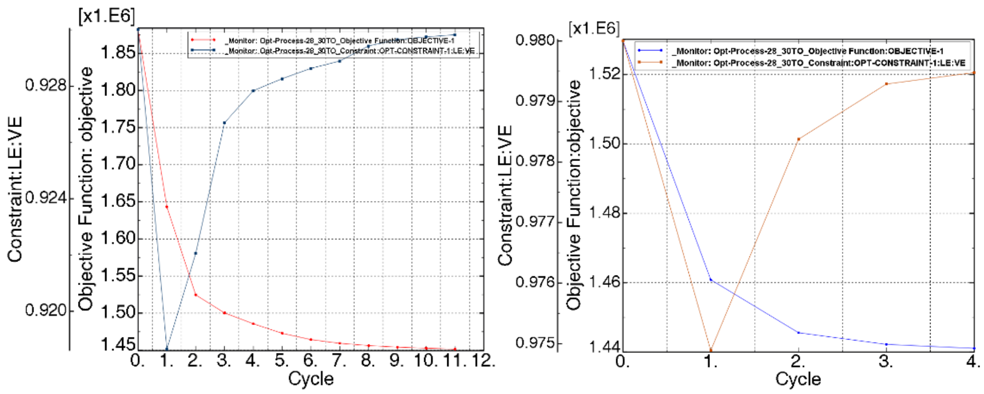
$\frac{\sigma w_n}{\sigma s_n} = \begin{bmatrix} 2.00 \\ 2.00 \end{bmatrix}$

Through Matlab program, we can obtain:

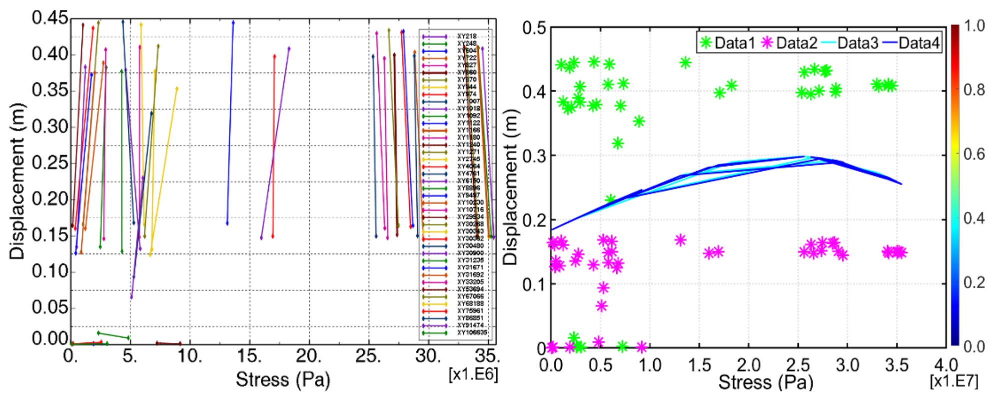
$$\{\triangle\,\sigma\}_k^v = \begin{bmatrix} 1.21\times10^7 & 1.20\times10^7 & 1.03\times10^7 & 9.80\times10^6 & 9.73\times10^6 \\ 9.58\times10^6 & 9.66\times10^6 & 7.90\times10^6 & 6.14\times10^6 & 4.07\times10^6 \end{bmatrix}$$

The conclusion of mathematical model analysis is: Stress = 35,375,944Pa > interval data (Stress < 34,938,088Pa); Displacement = 0.171m < interval data (Displacement < 0.177m); Sensitivity = 12,117,606.10 > interval data (Sensitivity < 1,093,243.26). After comparing the data, it can be concluded that stress and sensitivity are outside the constraint interval.

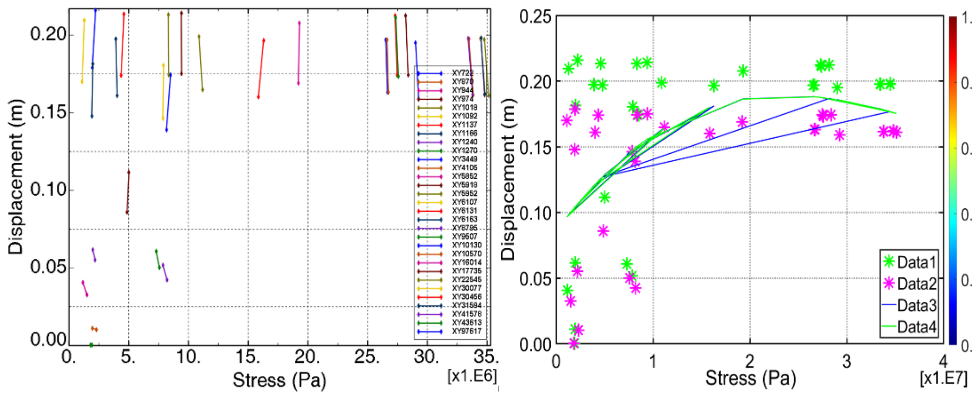
Then, the volume constraint was adjusted to 98%, and 5 iterative design cycles were completed (Figure 5.23-a). Maximum stress = 35,375,900Pa > 34,938,088Pa (beyond interval constraints); Displacement = 0.171,269,014m < 0.176,959,679m; Sensitivity = 12,563,418.25 > 1,093,243.26 (beyond interval constraints). After fitting 32 groups of test data, it shows that the internal



(a) (b)



(c) (d)



(e) (f)

Figure 5.23. TO analysis of 28#~30#. (a) finite element iterative analysis (93%). (b) finite element iterative analysis (98%). (c) analysis of stress and displacement (93%). (d) fitting analysis of stress and displacement (93%). (e) analysis of stress and displacement (98%). (f) fitting analysis of stress and displacement (98%).

Sources: Own elaboration, and anaiysis used the Abaqus software.

discreteness of the structure is widely distributed, and the main structure is not damaged, but two constraint indicators exceed the standard (Figures 5.23-c, d).

At the third time, the volume constraint was adjusted to 93%, and 11 iterative design cycles were completed (Figure 5.23-b). Maximum stress = 35,464,416Pa > 34,938,088Pa (beyond interval constraints); Displacement = 0.168m < 0.177m; Sensitivity = 11,940,097.020 > 1,093,243.26 (beyond interval constraints). After fitting 42 groups of test data, it shows that the internal discreteness of the structure is widely distributed, and the main structure is not damaged, Still, two constraint indicators exceed the standard (Figures 5.23-e, f).

Final conclusion: three TO analyses of 93%, 95%, and 98% were conducted for 28#-30#, respectively, and all the constraint parameters obtained exceeded the standard. It was determined that 28#-30# did not meet the standards of TO design specifications.

5.3.4. LCA, LCC and SIA analysis of SD

The conclusions obtained in the study in 5.3.3 show that: the volume of JMB's 32# can be optimized by 10% again, excluding pile foundation.

$V_{\text{concrete}} = (V_{\text{Pier base}} + V_{\text{Pier column}}) \times 10\% = (614.611,2+1,027.70) \times 10\% =$ 164.23m^3.

After calculation and analysis, a total of 164.23m^3 of reinforced concrete materials are saved, and openLCA1.10.3 software is used to analyze LCA and SIA data (Table 5.10). LCA decreased by 12,110.37 t, accounting for 0.063,89% of the original total. The total amount of SIA is 1,115.14 1000 Mrh, accounting for 0.034,2% of the actual total. The total amount of LCC is 220,461.56CNY, accounting for 0.0654% of the original total cost.

Table 5.10. LCA and SIA of JMB (reduce data)

Code	Name	Unit (eq)	Number of LCA (JMB)
1	Abiotic depletion	kg Sb	137.84
2	Acidification	kg SO_2	114.14
3	Eutrophication	kg PO_4-	38.66
4	Fresh water aquatic ecotox	kg 1,4-DB	12,879.80
5	Global warming (GWP100)	kg CO_2	49,717.10
6	Human toxicity	kg 1,4-DB	13,119.40
7	Marine aquatic ecotoxicity	kg 1,4-DB	12,031,000.00
8	ODP	kg CFC-11	0.002,0
9	Photochemical oxidation	kg C_2H_4	5.04
10	Terrestrial ecotoxicity	kg 1,4-DB	3,360.61
Code	**Name**		**SIA (Mrh)**
1	Anticompetitive conduct or monopoly legislation		31,018.9
2	Association and bargaining rights		4,066.53
3	Biomass consumption		4,947.38
4	Certified environmental management system		26,146.4
5	Child Labour, female		10,793.8
6	Child Labour, male		12,778.5
7	Child Labour, total		12,091.7
8	Corruption (100)		270,538
9	Dalys due to air and water pollution		1,168.75
10	Drinking water coverage		12,122.4
11	Education		20,271.2
12	Fair Salary		15,029.5
13	Fatal accidents (100)		81,111.7
14	Fossil fuel consumption		311.062
15	Frequency of forced labour		3,847.08
16	Gender wage gap		13,118.7
17	Goods produced by forced labour		40.094

18	Health expenditure	16,199.7
19	Illiteracy (100)	181,288
20	Indigenous rights	5,919.63
21	Industrial water depletion	129,795
22	International migrant stock	12,930.1
23	International migrant workers (in the sector/ site) (100)	42,157.8
24	Minerals consumption	2,181.93
25	Net migration	45.1629
26	Non-fatal accidents	7,521.05
27	Pollution	8,217.21
28	Safety measures	9,982.26
29	Sanitation coverage (100)	100,823
30	Social security expenditures	11,618.1
31	Trade unionism	26,881.9
32	Trafficking in persons	4,154.32
33	Unemployment	2,179.05
34	Violations relevant laws	1,824.19
35	Work times/per/week	329.587
36	Workers/natural disasters	1,639.64
37	Youth illiteracy	30,048.5

Sources: Own elaboration, and anaiysis used the OpenLCA software.

5.4. Management optimization assessment of JMB

According to the theoretical model and influencing factors of project management in 4.3 and 4.4, a careful and experienced project manager and project team are required to participate in the project planning and implementation of the super central bridge (total length of the bridge is more than 1,000m, specified in JTG D60-2015), to obtain the best economic benefits. In 5.1, the project management model of the JMB construction stage is implemented according to the project organization design. The general construction schedule of the leading project is determined by the construction unit (investor). The engineering has specific construction environment requirements. This section mainly analyzes the project management model and optimization of supporting auxiliary facilities that significantly impact the main project, including production, transportation, and installation of a T-beam fabrication yard, production and installation of a small component plant, and production and supply supporting concrete.

5.4.1. Sustainability analysis for project management

Firstly, based on engineering organization design, the T-beam prefabrication and installation (Figure 5.24). The original project management models in 4.3 and 5.1 is to start the installation of T-beams in the director of +0#~31# and complete the production and installation of 410 T-beams before completing the main bridge on February 10, 1999. The T-beams (with a total of 80) are transported across the main bridge to the installation position by the beam transport truck to complete the installation task of 35#~43#.

The minor component plant is set in the same area as the T-beam fabrication yard, convenient for management and the transportation and processing of concrete, reinforcement, and materials. It mainly produces anti-collision railings, drainpipes, and expansion joints of approach bridges (+0#~31#, 35#~43#). All construction teams should be responsible for producing and installing anti-collision railings, drainpipes, guardrails, and side railings of the main bridge (31#~35#): as and ladders bars, lightning rods inside the central tower.

focuses on the design, management, and production of the T-beam prefabrication yard. In 5.4, a domino evaluation model based on the entropy weight method is established to analyze the sustainability data of the beam factory.

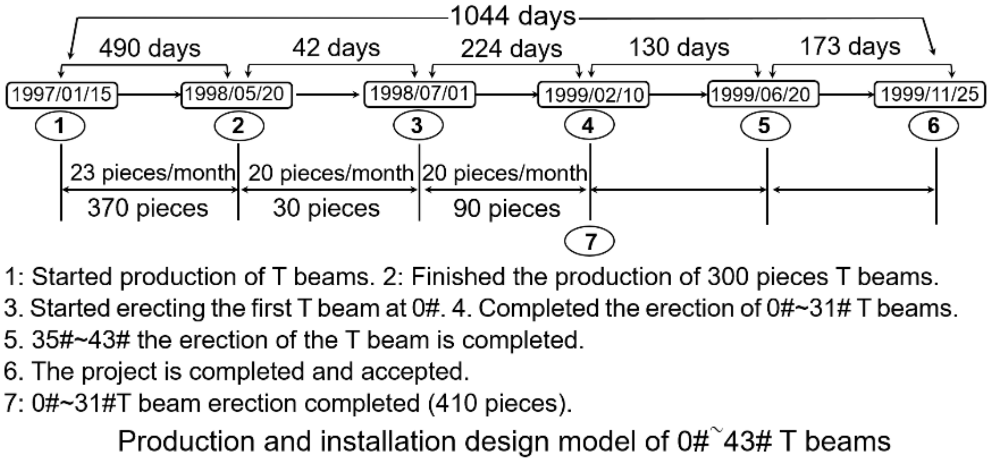


Figure 5.24. Data analysis model of +0#~43# T beams.

Sources: Own elaboration.

5.4.1.1 Data of LCC

According to the original project management model in 5.1, LCC mainly includes an office area, living area, two # mixing plants, component plant, T-beam reinforcement processing area, T-beam prefabrication area, and girder storage area of the beam factory. The design should ensure that the front beam factory of T-beam installation can meet the requirements of storing 400 girders, with two layers and 200 rafters on each layer, on July 1, 1998 (Figure 5.25). The cost shall also include all machinery, equipment, and materials. The calculation model is the same as 5.2.1.

1.Concrete production factory. **2**. Living and accommodation area. **3**. Steel and concrete component factories. **4**. T beam reinforcement cage binding area. **5**. T beam production area. **6**. T beam storage beam area. **7**. Ring road. **8**. 80 t gantry crane. 9. 0# abutment.

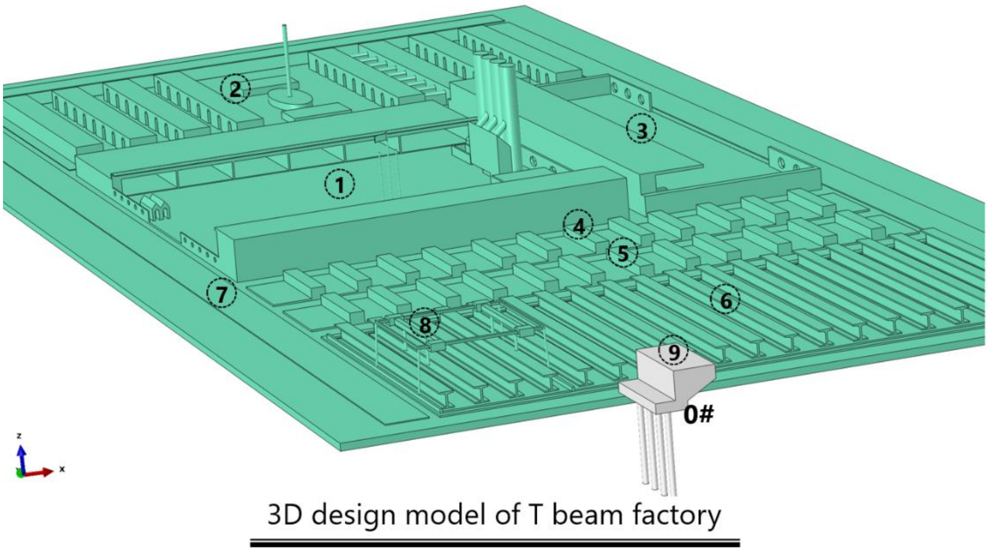


Figure 5.25. 3D model of concrete factory.

Sources: Own elaboration, and anaiysis used the Abaqus software.

The production cycle of the T-beam plant is 756 days, with a total of 95 management, experiment, and operation personnel. Each T-beam is produced according to the 9-day cycle:

a) One day for formwork erection and installation.

b) One day for concrete pouring.

c) Five days for the initial setting.

d) One day for formwork tensioning and removal.

The two # mixing plant supplies the concrete for the beam factory and the construction site, and the laboratory manages all tests in the beam factory. Table 5.11 shows the final budgeted cost, totaling 31.1798 million CNY, including the mechanical equipment of the beam factory and the laboratory. The cost of T-beam installation equipment shall be calculated separately: one SDLB double-guided bridge girder erection machine is 563,000 CNY (120 t); one beam transport truck is 165,000 CNY (120 t). The girder erection is installed from 0# abutment, with two side girders and eight middle girders for each span, totaling 10. On average, 2 T-beams are installed every day. The final comprehensive cost is 31.9078 million CNY.

The budget cost of the above LCC model analysis is calculated according to the original design implementation scheme, and the optimized project management model is analyzed in 5.4.2.

Table 5.11. LCC of T beam factory

Number	Name	Calculation method	JMB (CNY)
1	Labor Costs	Quota × working days	6,822,900.00
2	Direct Costs	Labor + Material+ Mechanical	8,342,765.58
3	Equipment Purchase Costs	1.899% × 1	158,429.12
4	Measures Costs	4.381% × 1	298,911.25
5	Enterprise management fees	4.143% × 2	345,640.78
6	Regulation fees	30.65% × 1	2,091,218.85
7	Profits	7.42% ×5	25,646.55
8	Taxes	10% × (2+...+7)	1,126,261.21
9	Special expenses	Stanard+1.5% × (2+...+7)	9,818,631.12
10	Compensation fees for land use and demolition	0.06381 × (2+...+9)	2,896,229.14
11	Other costs of engineering con-struction	3.14% × 2	90,941.59
12	Preparation cost	3% × 2	250,282.97
13	Loan interest during construction period	6.1% × (2+...+12)	5,734,860.55
14	The basic cost of the project	(1+...+13)	31,179,818.70

Sources: Own elaboration.

The optimization model reduces machining processes and procedures based on new design schemes and site planning, significantly reducing costs and economical expenses. Among them, labor, mechanical equipment, and labor costs have been reduced, and work efficiency has been improved. The superiority of the project management model is brought into play.

Paradigm criteria for the project management model are: cost savings, efficiency improvements, quality and schedule assurance.

5.4.1.2 Data of LCA

LCA analysis is conducted within the area agreed upon in 5.4.1. For example, the model study of T-beam is not included (the evaluation was completed in 5.2.2). The quantity of all personnel, materials, and equipment shall be analyzed by the model in 5.1.1 and Figure 5.25.

Table 5.12 shows the impact data of the T-beam factory and component plant emissions. The maximum emissions are marine aquatic ecotoxicity = 372,100 t, human toxicity = 598.15 t, and GWP100 = 435.15 t, totaling 373,327.47 t.

The loss of fossil energy materials in the construction industry has resulted in the discharge of a large amount of marine pollution, toxic gases, and liquids, resulting in the destruction of the marine environment and the greenhouse effect. Achieving sustainable development is not an industry's environmental governance but technological production and energy-saving equipment updates.

Table 5.12. LCA of T beam factory

Code	Name	Unit (eq)	Number of LCA (JMB)
1	Abiotic depletion	g Sb	715.80
2	Acidification	g SO_2	1,299.790
3	Eutrophication	g PO_4-	654.101
4	Fresh water aquatic ecotox	1,4-DB	215,792.00
5	Global warming (GWP100)	CO_2	435,150.00
6	Human toxicity	1,4-DB	598,147.00
7	Ecotoxicity of marine aquatic	1,4-DB	372,072,000.00
8	Ozone layer depletion (ODP)	g CFC-11	0.17
9	Photochemical oxidation	g C_2H_4	1,002.29
10	Terrestrial ecotoxicity	g 1,4-DB	2,708.270

Sources: Own elaboration.

5.4.1.3 Data of SIA

Table 5.13. SIA of T beam factory

Code	Name	SIA (Mrh)
1	Anticompetitive conduct or monopoly legislation	33,723.80
2	Association and bargaining rights	70,976.50
3	Biomass consumption	23,295.80
4	Certified environmental management system	148,620.00
5	Child Labour, female	242,949.00
6	Child Labour, male	260,512.00
7	Child Labour, total	252,660.00
8	Corruption	3,407,590.00
9	Dalys due to indoor and outdoor air and water pollution	-1,790,060.00
10	Drinking water coverage	220,464.00
11	Education	205,358.00
12	Fair Salary	160,243.00
13	Fatal accidents	1,609,590.00
14	Fossil fuel consumption	3,257.24
15	Frequency of forced labour	48,694.10
16	Gender wage gap	34,095.00
17	Goods produced by forced labour	38.90
18	Health expenditure	285,131.00
19	Illiteracy	4,167,900.00
20	Indigenous rights	42,386.70
21	Industrial water depletion	166,273.00
22	International migrant stock	1,389,100.00
23	International migrant workers (in the sector/ site)	1,389,100.00
24	Minerals consumption	11,456.80
25	Net migration	398.75
26	Non-fatal accidents	189,109.00
27	Pollution	181,210.00
28	Safety measures	33,710.30
29	Sanitation coverage	2,043,760.00
30	Social security expenditures	212,930.00
31	Trade unionism	222,502.00
32	Trafficking in persons	47,435.20
33	Unemployment	30,488.50
34	Violations of employment laws and regulations	26,539.80
35	Weekly hours of work per employee	3,214.47

36	Workers affected by natural disasters	19,112.10
37	Youth illiteracy	651,883.00

Sources: Own elaboration.

Table 5.13 shows that the total SIA data generated by the T-beam factory and supporting facilities are 16,045,647.96 Mrh. The first three are Illiteracy = 4,167,900.00; Corruption = 3,407,590.00; Sanitation coverage = 2,043,760.00; Fatal accidents = 1,609,590.00; International migrant stock = 1,389,100.00; Health expenditure = 285,131.00; Child Labour, male = 260,512.00; Child Labour, female = 242,949.00; Drinking water coverage = 220,464.00. Dalys due to indoor and outdoor air and water pollution = -1,790,060.00. Data show that education and corruption are still the core issues perplexing the development of all Asian countries (Warf, 2016); poverty, illiteracy, and cultural norm play a catalytic role and are closely related to economic and political indicators. In particular, corruption in the region will be fatal to national development. The top five indicators in the data analysis are the core indicators of community influencing factors, mainly public service, and social supervision departments, reflecting the impact and importance on the community.

5.4.2. Management of sustainable optimization

It can be found from the research process in 5.4.1 that the influencing factors can be reduced from the personnel, progress, environment, materials, machinery, and equipment. Materials and machines have been analyzed in 5.3. Other impacts are directly related to project management, so the paradigm management model must be established according to the adjustment and robustness of the engineering environment. In 4.3.1 and 4.3.3, it is concluded that the optimal model of case optimization is to find out the most critical path, which is the core part of restricting the project sustainability. Figure 5.3 shows that the construction process of a CSB dramatically impacts the overall progress. After the central bridge paradigm is determined, the robustness of supporting facilities such as the approach bridge and T-beam factory can be planned again.

The project management adjustment model is planned as follows: Figure 5.26 shows three key route design schemes. The main bridge construction period (31#-35#) affects the overall T-beam installation period based on meeting each process.

Plan **1**:

a) Complete the installation of +0#-31# T-beams.

b) Meet the navigation requirements of the Xi Jiang River.

c) Disconnect the construction access road.

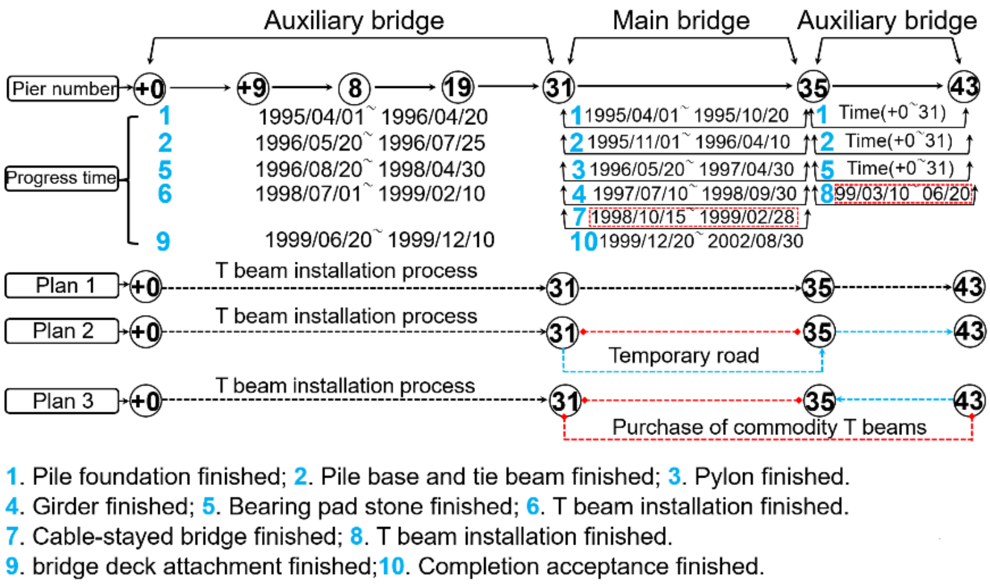


Figure 5.26. T beam installation design model.

Sources: Own elaboration.

After completing the 31#-35# girder, the beam transport truck transports the girder through the main bridge for 35#-43# T-beam installation (the analysis has been completed in 5.4.1).

Plan **2**: Complete the installation of +0#-31# T-beam, select other roads to transport the T-beam to 35#, and complete the installation of 35#-43#T-beam.

Plan **3**: Complete the installation of +0#-31#T-beam, select other roads to transport the T-beam to 43# (A total of 80 T-beams should be bought), install from 43# to 35# and complete the installation of 43#-35# T-beam.

Plan 2 and Figure 5.26 show that the project progress can ensure that the T-beams can be installed within six time periods after solving the road problem. The 7 and 8 project management plans are optimized to save the construction period. In Plan 3, commercial T-beams are directly purchased in the surrounding areas of 43# for the installation. A total of 80 T-beams should be bought, which can optimize the construction period of 198 days. According to the mathematical model of the domino probability indicator in 4.4.2, implementing the two plans will lead to domino changes in LCC, LCA, and SIA.

5.4.2.1 Plan one

The analysis is as follows: Plan 1: according to the budget method, the labor cost in LCC is reduced, and the construction period is saved by 157 days. The nearest river-crossing bridge - Zhaoqing - Xijiang Bridge (completed and passed in April 1987) is selected. The distance from JMB is 62km. The speed of heavy-duty beam transport trucks and no-load beam transport trucks is 4.5km/h and 50km/h, with the oil consumption of 19.76L/h and 14L/h under the power of 80kw.

N_{diesel} = 62/4.5×19.76+62/50×14 = 289.61L (the transportation distance is 124km, which is calculated according to the installation speed of 1 piece/day).

The total oil consumption is 289.61×80 = 23168.71L×0.84kg/L = 19,461.72kg.

According to the budget quota, the final LCC is -519,150.63CNY (the cost can be saved according to this plan).

LCA analysis data: the research process shows that it is mainly labor cost and oil saving of mechanical equipment, which shortens the installation work cycle for a long time. According to Table 5.14, 266,344.75 t of LCA are reduced, accounting for 1.404,7% of the actual total emissions.

Table 5.14. LCA data of management optimization (plan one)

Code	Name	Unit	Number of LCA (JMB)
1	Abiotic depletion	g Sb eq	869.06
2	Acidification	g SO_2 eq	791.62
3	Eutrophication	g PO_4- eq	375.60
4	Fresh water aquatic ecotox	1,4-DB eq	315,800.00
5	Global warming (GWP100)	CO_2 eq	130,874.00
6	Human toxicity	1,4-DB eq	488,140.00
7	Marine aquatic ecotoxicity	1,4-DB eq	265,407,000.00
8	Ozone layer depletion (ODP)	g CFC-11 eq	0.01
9	Photochemical oxidation	g C_2H_4 eq	55.72
10	Terrestrial ecotoxicity	g 1,4-DB eq	846.37

Sources: Own elaboration.

The LCA data is analyzed with open software, and the corresponding optimization quantity is reduced based on the original data. The calculation conclusion is obtained through the Monte Carlo simulation analysis of the new data.

According to the impact data analysis of SIA in Table 5.15, a total of 22,147,099.52 Mrh of SIA are reduced, accounting for 0.679% of the original total.

Table 5.15. SIA data of management optimization (plan one)

Code	Name	Number (Mrh)
1	Anticompetitive conduct or monopoly legislation	41,265.50
2	Association and bargaining rights	71,394.30
3	Biomass consumption	24,666.80
4	Certified environmental management system	376,947.00
5	Child Labour, female	369,427.00
6	Child Labour, male	417,981.00
7	Child Labour, total	380,115.00
8	Corruption	3,774,690.00
9	Outdoor air and water pollution of dalys	37,737.80
10	Drinking water coverage	372,027.00
11	Education	352,908.00
12	Fair Salary	137,559.00
13	Fatal accidents	712,891.00
14	Fossil fuel consumption	5,238.78
15	Frequency of forced labour	60,584.00
16	Gender wage gap	297,009.00
17	Goods produced by forced labour	340.39
18	Health expenditure	473,899.00
19	Illiteracy	7,270,280.00
20	Indigenous peoples rights	75,156.50
21	Industrial water loss	126,940.00
22	Number of international migrant	97,422.90
23	International workers exchange (in the sector/ site)	622,588.00
24	Minerals depietion	41,000.90
25	Net migration	685.59
26	Non-fatal accidents	340,980.00
27	Pollution	119,292.00
28	Safety measures	93,935.20
29	Sanitation coverage	3,517,590.00
30	Social security expenditures	359,940.00
31	Trade unionism	363,001.00
32	Trafficking in persons	60,448.20
33	Unemployment	38,849.30
34	Violations relevant laws	17,352.00
35	Work times/per/week	4,041.06

36	Workers/natural disasters	12,966.30
37	Youth illiteracy	1,077,950.00

Sources: Own elaboration.

5.4.2.2 Plan two

Plan 2: the purchased commercial T-beams are directly transported to 43# for installation. According to the three pieces/day plan, the construction period can be saved by 210 days. The purchase price and the production price of the T-beam are calculated according to the quota, and there is no price difference. The manufacturer is responsible for the transportation of T-beams without other oil consumption.

Table 5.16. LCA data of management optimization (plan two)

Code	Name	Unit (eq)	Number of LCA (JMB)
1	Abiotic depletion	g Sb	342.24
2	Acidification	g SO_2	645.19
3	Eutrophication	g PO_4-	346.17
4	Aquatic ecotox of fresh water	1,4-DB	116,028.00
5	Global warming (GWP100)	CO_2	224,921.00
6	Human toxicity	1,4-DB	326,787.00
7	Aquatic ecotoxicity of marine	1,4-DB	199,786,000.00
8	Ozone layer depletion (ODP)	g CFC-11	0.01
9	Photochemical oxidation	g C_2H_4	51.96
10	Ecotoxicity of terrestrial	g 1,4-DB	1,447.29

Sources: Own elaboration.

According to the budget quota, Plan 2 can save – 860,787.12CNY of LCC. LCA data analysis: Plan 2 can reduce the installation time without increasing other costs. 80 T-beams can be installed directly. According to Table 5.16, the total amount is 200,456.57 t, accounting for 1.057% of the total emissions.

Due to the reduction of material loss and the use of equipment fuel, the reduction of SIA data in Plan 2 is also low, SIA=16,668,365.12 Mrh, accounting for 0.511%. See Table 5.17 for detailed data.

The key influencing factors in SIA data analysis are corruption and illiteracy, and this is also the basis for the community to improve laws and regulations. Any country with imperfect laws will face many communities that affect life and production.

Table 5.17. SIA data of management optimization (plan two)

Code	Name	Number of SIA (Mrh)
1	Anticompetitive conduct or monopoly legislation	31,057.27
2	Association and bargaining rights	53,732.83
3	Biomass consumption	18,564.74
4	Certified environmental management system	283,698.11
5	Child Labour, female	278,038.40
6	Child Labour, male	314,581.14
7	Child Labour, total	286,082.41
8	Corruption	2,840,909.76
9	Dalys due to air and water pollution	28,402.25
10	Drinking water coverage	279,995.21
11	Education	265,605.86
12	Fair Salary	103,529.75
13	Fatal accidents	536,536.51
14	Fossil fuel consumption	3,942.81
15	Frequency of forced labour	45,596.77
16	Gender wage gap	223,535.12
17	Goods produced by forced labour	256.18
18	Health expenditure	356,666.19
19	Illiteracy	5,471,763.08
20	Indigenous rights	56,564.34
21	Industrial water depletion	95,537.67
22	International migrant stock	73,322.49
23	International migrant workers (in the sector/ site)	468,572.60
24	Minerals consumption	30,858.13
25	Net migration	515.99
26	Non-fatal accidents	256,628.60
27	Pollution	89,781.63
28	Safety measures	70,697.57
29	Sanitation coverage	2,647,410.98
30	Social security expenditures	270,898.29
31	Trade unionism	273,202.06
32	Trafficking in persons	45,494.57
33	Unemployment	29,238.79
34	Violations relevant laws	13,059.47
35	Work times/per/week	3,041.39
36	Workers/natural disasters	9,758.71
37	Youth illiteracy	811,287.46

Sources: Own elaboration.

5.5. Innovation in case Optimization Research

After obtaining the data in 5.4, the fundamental research and analysis process is completed, and two types of optimization and innovation analysis models are adopted, focusing on TO of 3D entity structure and optimization and innovation of the project management model.

The innovations herein are as follows:

a) The case selected is representative in this field, has all the conditions of complex super significant bridges, and its robustness to the theoretical model of the full text is verified.

b) Starting from analyzing the characteristics of each stage of the whole life cycle, this study demonstrates the robustness of the process, analyzes the model data according to the sustainable operation of the actual bridge, and obtains the sustainability data.

c) TO research process overcomes the problem of a vast grid model. It completes the whole bridge's 3D finite element coupling analysis under the influence of static load, dynamic load, and uncertain load, involving 3,358,023 groups of elements. Although the data are unique, it improves the paradigm of research structure. Based on the detailed data, the transmission and distribution of internal stress and energy of micro and components can be seen clearly.

d) The diversity of mathematical models is judged through TO. The change of bridge stress under multi-standard load is studied through the multi indicator strategy of fitting, discreteness, structural safety, integrity, and sensitivity, it provides sufficient theoretical scientific basis for optimization analysis.

e) The development and application of multi-objective optimization model under the minimum project management show the 3D management model of the central bridge tower, girder, and approach bridge. Vividly reflecting the construction process of JMB and innovatively establishing the domino evaluation model based on the entropy weight method. By transforming various project management modes, project management sustainability is realized.

The final best project management model is: TO design optimization + project management plan 1. The sustainability data of reduction are: LCC = 739,612.19CNY, LCA = 278,455.12t, SIA = 23,262,239.52Mrh; TO design optimization + project management plan 2. The sustainability data of reduction are: LCC = 1,081,248.68CNY, LCA = 212,566.94T, SIA = 17,783,505.12Mrh. The two combined models have different characteristics (Table 5.18).

Table 5.18. Data of SD model

Code	Model	Name	Unit	Number
1	Original design	LCC	CNY	336,950,603.90
2		LCA	t	18,961,138.50
3		SIA	Mrh	3,261,560,462.00
4	TO	LCC	CNY	220,461.56
5		LCA	t	12,110.37
6		SIA	Mrh	1,115,140.00
7	Plan one of management	LCC	CNY	519,150.63
8		LCA	t	266,344.75
9		SIA	Mrh	22,147,099.52
10	Plan two of management	LCC	CNY	860,787.12
11		LCA	t	200,456.57
12		SIA	Mrh	16,668,365.12

Sources: Own elaboration.

From Figure 5.27, it can be seen that the two different paradigms have their own characteristics. From the economic perspective, the second model is more

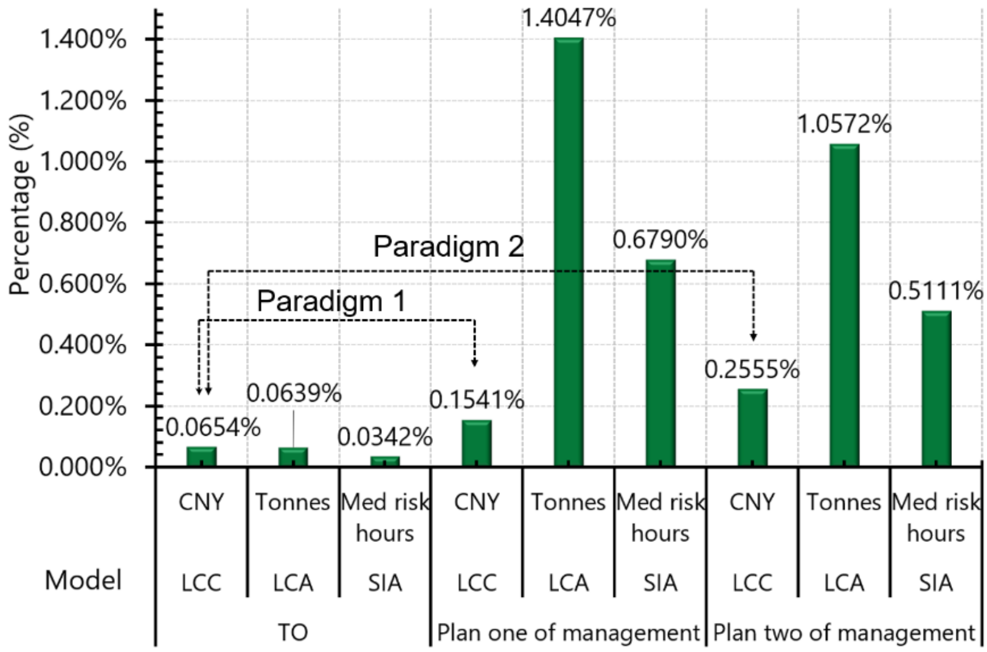


Figure 5.27. The ratio of the two paradigm models to the total.

Sources: Own elaboration.

reasonable, and the solution cost is 1.081,2 million CNY.

From reducing ecological impact, the first model is more reasonable. The emission reduction is LCA = 65,888.18 t, SIA = 5,478,734.40 Mrh.

5.6. Summary of this chapter

This chapter is the crucial part of the thesis, which demonstrates the robustness of theoretical models in Chapter 4 through the analysis of typical cases. This chapter starts with the finite element coupling analysis of bridges, gradually advances the topology optimization coupling analysis of micro and macro structures, and analyzes the sustainability of each part of the bridge structure according to the established mathematical model. Secondly, the TO theoretical model and project management model are applied to study the component optimization, which lays a foundation for the overall sustainability evaluation of JMB and forms a research process and paradigm conclusion. Finally, this chapter summarizes the advantages of different models and the research innovation theory. They are making the research system more perfect and systematic and highlighting the emphasis of the whole thesis.

Chapter 6. Conclusions

6.1. Conclusions of the thesis

The thesis starts with the emission data analysis of the top 14 countries in terms of global CE and studies the per capita CE and environmental governance status of the 14 countries. The author analyzes the current status of international SD literature publication and predicts future research directions and fields, proving the necessity of scientific research cooperation and cross-regional research. Given the influence of discrete, complex, uncertain, and other interference factors of the current SD research objects, a complete mathematical theoretical model is established for LCC, LCA, and SIA, especially, research has improved the impact and interference of sudden and sensitive factors on sustainable assessment.

The mathematical models established in the thesis include： A multi-level planning impact model to solve the problem of data dispersion and uncertainty. Establish TO multi-factor control and multi-level strategy model to improve optimization efficiency and quality; proposed project management optimization compensation elements and entropy weight method domino; The domino evaluation model addresses the uncertainty, dispersion, disturbance, and mutation of event influencing factors. The case study starts with coupled finite element analysis of bridges, robust finite element analysis of microscopic and 3D structures, carries out the systematic model calculation and derivation analysis for component optimization, and finally achieves the goal of comprehensive optimization.

After the finite element coupling analysis and scientific evaluation, the bridge has a reduction of 220,461.56CNY in LCC, accounting for 0.065% of the total cost; a decrease of 12,110.37t in LCA, accounting for 0.064% of the whole original emissions; a reduction of 1,115,140Mrh in SIA, accounting for 0.034% of the total impact data.

According to the data of the best plan after evaluation by the establishment of the project management optimization model: the reduction in LCC is 860,787.12CNY, accounting for 0.256% of the total cost; the decrease in LCA is 266,344.75t, accounting for 1.405% of the whole original emission; the reduction in SIA is 22,147,099.52Mrh, accounting for the total 0.679% of the impact data.

With the continuous changes in the world pattern, global greenhouse gas emissions are still on the rise (Lin et al., 2019), which has an increasingly severe impact on the natural environment and living environment of people around the world. There is an urgent need for scientific researchers to apply innovative research methods and theoretical models to transform the world, change old production technologies and manufacturing methods, and create green tools and products for the new industrial revolution. The thesis displays a complete set of systematic theoretical research and case analysis, providing theoretical mathematical models and scientific data for scientific research of the same type and in the same field, which is convenient for other researchers to refer to and learn from.

Research needs to continue to improve and strengthen research aspects:

a) The application of different mathematical theoretical models is restricted by certain research environment conditions, whether it needs to be expanded or strengthened.

b) Whether it is necessary to increase the complexity of the research case selection and conduct a comprehensive study of the two-tower, three-tower, and multi-tower cable-stayed bridges to reflect better the practicability and robustness of the established research theoretical model.

c) The research process requires technical support with particular engineering management and construction experience to understand and apply the theoretical model better. After all, the ultimate goal of any scientific research theory is commercialization.

d) Whether the research environment and case are selected as a bridge in China and whether it is suitable for other countries' manufacturing and production environment needs to be confirmed by relevant research.

e) The industrialized construction industry is the future of the development of the construction industry. Some of the modern industrial construction methods and equipment used are analyzed in the theoretical research system. Because the characteristics of construction projects determine the differences in project organization, it is necessary to study, analyze and identify the theoretical model system. Practicality.

f) The research has been proofread and checked many times, and minor grammatical inaccuracies and unclear narratives need to be improved.

Features of the thesis:

a) The research model is from big to small, from surface to point. From the global environmental impact results to the specific analysis of the bridge's environmental impact contribution value, it fully reflects the effective combination of macroscopic research and microstructure.

b) The theoretical model system of the study is diversified. The thesis establishes four huge mathematical theoretical models to solve the diversity of influencing factors, the sensitivity of control factors, the uncertainty of discrete data, and the domino effect of project interference factors. Systematize and normalize the overall research framework.

c) Interdisciplinary application, the thesis applies advanced mathematics, structural mechanics, fluid mechanics, damage mechanics, environmental science, economics, and management. The comprehensive application and innovation of theories related to various disciplines and research topics have realized the scientific notion of a vast theoretical model of research, which has laid a solid scientific foundation for the theoretical system of research.

d) The practicability and value of the research results. The author has rich experience in advanced engineering management and perfectly combines the theoretical research system and practical engineering cases to achieve the optimization goal of complex statically indeterminate structures. The case has practical guiding significance for this structure and establishes an application paradigm for similar structures.

e) The thesis proposes many innovative models and research systems, which provide new research ideas and methods for other researchers and expand the the future research methods and frameworks in this field.

Scientific research has no boundaries, and the construction industry's SD evaluation and design are even more difficult. The realization of green, environmental protection, low carbon, and energy saving will be a bright prospect for the sustainable construction of bridges now and in the future.

6.2. Post-research plan

The construction industry is full of challenges and opportunities in the future. It needs the rapid development of manufacturing and industrialization, the massive R&D, and the use of industrial science and technology, artificial intelligence, mechanical automation, building informatization, and industrial link digitization have all enhanced the development of the construction industry at different stages (Turner et al., 2021). How to better realize the SD of the construction industry? What is the best new strategy to reduce system pollutant emissions? What are the limitations of sustainability management techniques, monitoring, evaluation, and improvement techniques in future construction industry research? How to better use new equipment and innovative technologies to achieve sustainable control goals in the initial stage (Hong et al., 2021)? Qualitative and quantitative analysis of the final sustainable data of construction projects through the paradigm of monitoring, evaluation, and improvement, continuously Summarize and improve research strategies and methods, break old management models and performance evaluation standards, and innovate thinking.

The following ideas are proposed for the future research direction of the current SD of the construction industry:

a) Research on the direction and main influencing factors of sustainable future development of the construction industry.

b) The combination of highly developed industrialization and sustainable and practical innovation in the construction industry.

c) Durability and environmental friendliness of materials with sustainable impact paradigms.

d) The informatization of the blockchain block and the robustness of the construction industry.

e) Cross-regional sustainable optimal strategy for the construction industry.

f) Ecological and climate impacts of global carbon transfer.

g) The future of non-renewable energy in the construction industry.

h) Research on the construction stage's paradigm model of informatization and industrialization project management.

i) Optimal planning and scientific layout of the construction of extra-large and complex projects.

j) Dynamically control and manage the consumption and optimization of human resources in the construction phase.

6.3. Summary of this chapter

First, the completeness and robustness of the theoretical model system of the thesis are explained through the comprehensive summary of this chapter, and some of the theoretical models have innovations and paradigms that represent the field. introducing each mathematical model's critical uses and features. The application data illustrates the sustainable impact data achieved after TO and management optimization, and the reduction data is low. The research model and ideas show many innovative theories and methods, solid foundations for the follow-up research work. Finally, thinking and directions for future essential research are proposed.

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Annex I Disclosure of results

Participation in conferences

Zhi Wu Zhou, Julián Alcalá, Víctor Yepes. "Bridge cabon emission based on fuzzy mathematics and grey correlation research and driving factor analysis and optimization"GSCAEE-2021.july 19-21,2021, barcelona,spain.

Zhi Wu Zhou, Julián Alcalá, Víctor Yepes. "Research on multi-criteria entropy method based on case mechanism of regional bridge maintenance management" 11th International Conference on Recycling & Waste Management July 26-27, 2022, Prague, Czech Republic.

Zhi Wu Zhou, Julián Alcalá, Víctor Yepes. "Coupling research on sustainable development of China's construction industry in the 21st century"; e "International conference on Climate Change and Human Health Impacts" which is going to be held during August 25-26, 2022 at Florida, USA.

Articles in research journals

ZHOU ZhiWu, ALCALÁ J, & YEPES V. (**2020**). 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*, Vol. 17, No. 16. https://doi. 10.3390/ijerph17165953.

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ZHOU ZhiWu, ALCALÁ J, KRIPKA M, & YEPES V. (**2021**). Life Cycle Assessment of Bridges Using Bayesian Networks and Fuzzy Mathematics. *Applied Sciences*, Vol. 11, No. 11, p. 4916, mai. https://doi.org/10.3390/app11114916.

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ZHOU ZhiWu, ALCALÁ J, & YEPES V. (**2022**c). Experimental Research on Diseases of Emulsified Asphalt Mortar Board for Ballastless Tracks, *Journal of Materials in Civil Engineering*, Vol. XX, p. XX, https://doi.org/10.1061/JMCEE7/MTENG-15149.

ZHOU Z W, ALCALÁ J, & YEPES V. (**2022**d) Research on sustainable development of regional construction industry based on entropy theory. *Sustainability*, Vol. 14, No. 16645; https://doi.org/10.3390/su142416645.

Chapters of books

Zhi Wu Zhou, Julián Alcalá, Víctor Yepes. "Bridge cabon emission based on fuzzy mathematics and grey correlation research and driving factor analysis and optimization"GSCAEE-2021.july 19-21,2021, barcelona,spain. https://webmail.upv.es/imp/view.php?actionID=view_attach&id=2&muid=%7B5%7DINBOX3367&view_token=1wdJExW5wAD6tXEJguSEUEm&uniq=1650353697756.

Pending publications

ZHOU Z W, ALCALÁ J, & YEPES V. (**2022**) Bridge construction project management and carbon impact assessment based on resilience theory. *Journal of Civil Engineering & Management*, (**Under review**).

ZHOU Z W, ALCALÁ J, MOACIR KRIPKA & YEPES V. (**2022**) Research on bridge sustainability assessment based on multi-coupling finite element model. *International Journal of Environmental Research and Public Health*. (**Under review**).

Publications in preparation

ZHOU Z W, ALCALÁ J, & YEPES V. Analysis of the influence of bridge on environmental entropy weight under thermoelastic coupling.

ZHOU Z W, ALCALÁ J, & YEPES V. Current situation and assessment of Carbon Leakage in construction industry - An example of China's foreign investment projects

Attend training and conferences

a) Completion of horizontal training courses: The first course: "Applied Research Methodology"; The second course: "High Standards For Scientific Production And Communication".

b) Scientific Forum: "CATEDRA HIDRALIA+UGR RED ANDALUZA CONTRA EL CAMBIO CLIMATICO COVID OPORTUNIDAD OAMENAZA PARA LOSODS" November 24, 2020; obtain the certificate.

c) Training Courses: "Webinar "Elsevier Pure: presentación técnica de producto" Thursday 29 October, 2020; obtain the certificate.

d) Training Courses: "Webinar: Como evaluar las publicaciones de su Universidad dentro de los Objetivos de Desarrollo Sostenible" Thursday 20 October, 2020; obtain the certificate.

e) Training Courses: "Webinar: ¿Por qué las organizaciones necesitan sistemas CRIS?El caso de Elsevier Pure" Thursday 13 October, 2020; obtain the certificate.

f) Attend: PROGRAMA FORMATIVO EN INICIACIÓN AL EMPRENDIMIENTO PARA INVESTIGADORES PREDOCTORALES ; "Comunicación efectiva para emprendedores: elevator pitch" ; 12 de noviembre de 2020; obtain the certificate.

g) Attend: PROGRAMA FORMATIVO EN INICIACIÓN AL EMPRENDIMIENTO PARA INVESTIGADORES PREDOCTORALES ; "Lean Startup. Emprende ligero, equivócate rápido, aprende barato", 10 de noviembre de 2020; obtain the certificate.

h) Attend: PROGRAMA FORMATIVO EN INICIACIÓN AL EMPRENDIMIENTO PARA INVESTIGADORES PREDOCTORALES; "Mind set emprendedor y competencias emprendedoras"; 02 de noviembre de 2020;obtain the certificate.

i) Attend: PROGRAMA FORMATIVO EN INICIACIÓN AL EMPRENDIMIENTO PARA INVESTIGADORES PREDOCTORALES; "Herra mientas básicas de inicio al emprendimiento: creación de un modelo de negocio", 05 de noviembre de 2020; obtain the certificate.

j) Attend: PROGRAMA FORMATIVO EN INICIACIÓN AL EMPRENDIMIENTO PARA INVESTIGADORES PREDOCTORALES; "Networking y redes sociales: marca personal vs. branding corporativo", 06 de noviembre de 2020; obtain the certificate.

k) Attend: "International Conference on Pollution Control ＆Sustainable" Institute of concrete science and technology, Spain. obtain the certificate.

l) Attend: "con pasaporte número EF0723781, ha participado en el evento VII Encuentro de Estudiantes de Doctorado de la UPV, realizado el día 7/7/22", y para que conste a los efectos oportunos, se expide el presente certificado.

Special reviewer's work (36 peer reviews)

a) "Archives of Civil and Mechanical Engineering" (WoS - Q1; Impact facter=4.042). Manuscript number: ACAM-D-21-00610; Title: "Effects of Deck-Abutment Pounding on the Seismic Fragility Curves of Box-Girder Highway Bridges"; Time: June 14.2021.

b) "Engineering, Construction and Architectural Management"(WoS - Q2; Impact facter=3.85). Manuscript number: ECAM-04-2022-0291; Title: "Water environment treatment PPP projects optimal payment mechanism based on multi-stage dynamic programming model"; Time: June 13.2022.

c) "Sustainability", (WoS - Q2; Impact facter=3.251). Manuscript number: Sustainability-1422767. Title: "Exergy based Lifecycle Assessment Model for Evaluating the Environmental Impact of Bridge: Principle and Case Study", Time: June 13.2022. Time: October 08.2021.

https://doi.org/10.3390/su132111804.

d) "Engineering, Construction and Architectural Management"(WoS - Q2; Impact facter=3.531). Manuscript number: ECAM-10-2021-0869; Title:

Project and Organization Factors of Government's Escalation of Commitment in PPP Project – Data from China; Time: February 26.2022.

e) "Processes", (WoS - Q3; Impact facter=2.847). Manuscript ID: processes-1472718. Title: "The View on Steelmaking Dusts and Sludges as Secondary Raw Materials–Analysis and Evaluation of the Characteristic Properties."; Time: November 11.2021.

f) "Journal of Open Innovation: Technology, Market, and Complexity", (CiteScore - Q1; Impact facter=3.8). Manuscript ID: JOItmC-1523024. Title: "Artificial Intelligent Technologies in the Construction Industry: How Are They Perceived and Utilized in Australia?."; Time: January 4.2022.

https://doi.org/10.3390/joitmc8010016.

g) "Sustainability", (WoS - Q2; Impact facter=3.251). Manuscript ID: sustainability-1568340. Title: "Economic Valuation of Improving Environmental Degradations in Korea Using Choice Experiment", Time: January 12.2022.

https://doi.org/10.3390/su14031600.

h) "Infrastructures", (CiteScore - Q2; Impact facter=2.5). Manuscript ID: infrastructures-1634912. Title: "Multidisciplinary investigations of a steel-concrete composite bridge", Time: March 17.2022.

https://doi.org/10.3390/infrastructures7040053.

i) "Econometrics", (CiteScore - Q2; Impact facter=2.5). Manuscript ID: econometrics-1695615. Title: "INFORMATION RECOVERY IN COMPLEX ECONOMIC BEHAVIOR SYSTEMS", Time: April 17.2022.

j) "IJERPH", (CiteScore - Q2; Impact facter=4.61). Manuscript ID: ijerph-1735492. Title: "The effects of environmental regulations on medical expenses: Evidence from China", Time: June 15.2022.

https://doi.org/10.3390/ijerph19137567.

k) "Sustainability", (WoS - Q2; Impact facter=3.251). Manuscript ID: sustainability-1794764. Title: "Assessment of the usability of some bio-based insulation mate-rials in double-skin steel envelops", Time: August 15.2022.

https://doi.org/10.3390/su141710797.

l) "Sustainability", (WoS - Q2; Impact facter=3.251). Manuscript ID: sustainability-1838417. Title: "Satisfaction with the Pedestrian Environment and its Relationship to Neighborhood Satisfaction in Seoul, South Korea", Time: July 22.2022.

https://doi.org/10.3390/su14159343.

j) ”IJERPH”, (CiteScore - Q2; Impact facter=4.61). Manuscript ID: ijerph-1924713. Title: ”Forced Transformation” or “Regulation Capture”—Research on the Interactive Mechanism between Environmental Regulation and Green Transformation of Dairy Farming Subject Production.” Time: September 26.2022.

https://doi.org/10.3390/ijerph191912982 (registering DOI).

k) “Sustainability”, (WoS - Q2; Impact facter=3.251). Manuscript ID: sustainability-1882743. Title: “The Roles and Synergies of Actors in the Green Building Tran-sition: Lessons from Singapore”, Time: October 14. 2022.

https://doi.org/10.3390/su142013264 (registering DOI)

Other work

a) Counsel the preparation of a graduate thesis.

Name：Cao, Zijian；The title of thesis: ”BRIDGE LIFE CYCLE ASSESSMENT AND BIM SOFTWARE APPLICATION OPTIMIZATION-RESEARCH ON ZHANJIANG BAY BRIDGE IN”. Master's Degree in Engineering of Roads, Canals and Ports.

Annex II. Copyright

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The authors declare no competing interests and the content of published articles.

Additional information

Additional datas Table 1. Symbolic statistics of thesis formulas

Formula code	Symbol	Description
Eq.2.1	u_1	LCC influencing factor.
	u_2	LCA influencing factor.
	u_3	SIA influencing factor.
Eq.2.2	r_{mn}	Fuzzy evaluation subset for each factor.
	B	The judgment data set.
	A	Fuzzy subset.
	R_i	The fuzzy subsets.
Eq.3.1	C_M	LCC economic cost (CNY).
	C_P	Cost at preparation stage (CNY).
	C_D	Cost at design stage (CNY).
	C_C	Cost at construction stage (CNY).
	C_U	Maintenance and service cost at use stage (CNY).
	C_d	Demolition and clean-up stage (CNY).
Eq.3.2	C_M^E	Total investment amount (CNY).
	$\sum_{T_0}^{T_6} C_N$	CN costs(CNY).
	CN	Construction and installation costs.
	$\sum_{T_0}^{T_4} C_D$	CLD costs (CNY).
	CLD	Compensation for land use and demolition.
	$\sum_{T_3}^{T_6} C_O$	OCE costs (CNY).
	OCE	Other costs of engineering construction.

	$\sum_{T_0}^{T_4} C_P$	PE cost (CNY).
	PE	Preparatory expenses.
	$\sum_{T_1}^{T_4} C_L$	Loan interest during the construction period.
Eq.3.3	$C_d(M,T)$	The cost incurred due to damage P in time range T (CNY).
	$T_1,\dots,T_6$	See Figure 3.3.
	T	Time range.
	n_d	The number of random events.
Eq.3.4	$C_d(M,T)^R$	The discrete cost included in C_M^E (CNY).
	$\sum_{T_2}^{T_3} C_{CN}$	The original cost incurred in the interval of $T\in(T_2, T_3)$ (CNY).
	C_I	Calculation of incurring cost (CNY).
	C_R	Cost of re-budget (CNY).
Eq.3.5	C_M^N	The final LCC economic cost (CNY).
Eq.3.6	M_L	Material LCA impact data (kg).
	M_n; M_m	The weights of n-m kinds of different materials (kg).
	μ_c; μ_d	The material production process loss rate (%).
	λ_c; λ_d	The material coefficient affecting the emission (kg/kg).
Eq.3.7	D_L	LCA impact data at the design stage (kg).
	P_n	The number of relevant design personnel (person-day).
	M_d	The number of materials in the design consumed and used (kg).
	μ_u	The material wastage rate in the design (%).
	M_l	The loss of relevant equipment and oil used at the design stage (kg).
	λ_p; λ_m	The emission coefficient of the environmental impact of personnel and equipment (kg/kg).
	$\sum M_O$	The design optimization rate (%).
Eq.3.8	C_L	The impact data at the construction stage (kg).
	P_c	The number of personnel at the construction and quality assurance stage (person-day).
	M_c^1	The quantity of other materials (excluding materials outside the scope of design drawings) during construction (kg).
	μ_b	The loss rate during construction (%).

	M_c^2	The amount of energy consumed by machinery and equipment used in construction (kg).
Eq.3.9	C_L^T	The impact data at the final construction stage (kg).
	μ_m	The reduction rate of project management model after using optimized management (%).
Eq.3.10	U_L	The impact data at the final use stage (kg).
	U_C	The maintenance cycle (T).
	C_t	The maintenance cost (CNY).
	T_i	The number of maintenance due to Uncertain factors.
	N_a	Unnatural damage.
	E_a	Earthquake disaster.
	F_a	Traffic accident.
Eq.3.11	D_L^d	The emission at the demolition stage (Kg).
	P_n	The total number of labor force (person-day).
	λ_p	The per capita emission coefficient (kg/person-day).
	E_n	The total energy consumed by equipment and machinery (kg).
	λ_e	The emission of each energy source (kg).
	λ_f	The energy loss rate of machinery (%).
	M_n	The total amount of material used (kg).
	λ_v	The emission of materials (kg).
	λ_t	The material wastage rate (%).
Eq.3.12	S_S^1	SIA impact data (CNY).
	SC_2	Medical costs (CNY).
	SC_3	The loss in income caused by death and disability (CNY).
	SC_4	The property loss caused by traffic accident (CNY).
	SC_5	The monetary cost per unit of travel time.
	SC_6	The additional service cost of the vehicle (CNY).
	SC_7	The loss in business income affected by the construction project (CNY).
	SC_8	The loss of labor productivity caused by construction noise (CNY).
	SC_9	The depreciation on properties caused by construction noise (CNY).
	SC_{10}	Accident administrative cost (CNY).
	SC_{11}	The loss in parking revenue (CNY).
Eq.3.13	S_S^2	SIA person impact data (day).

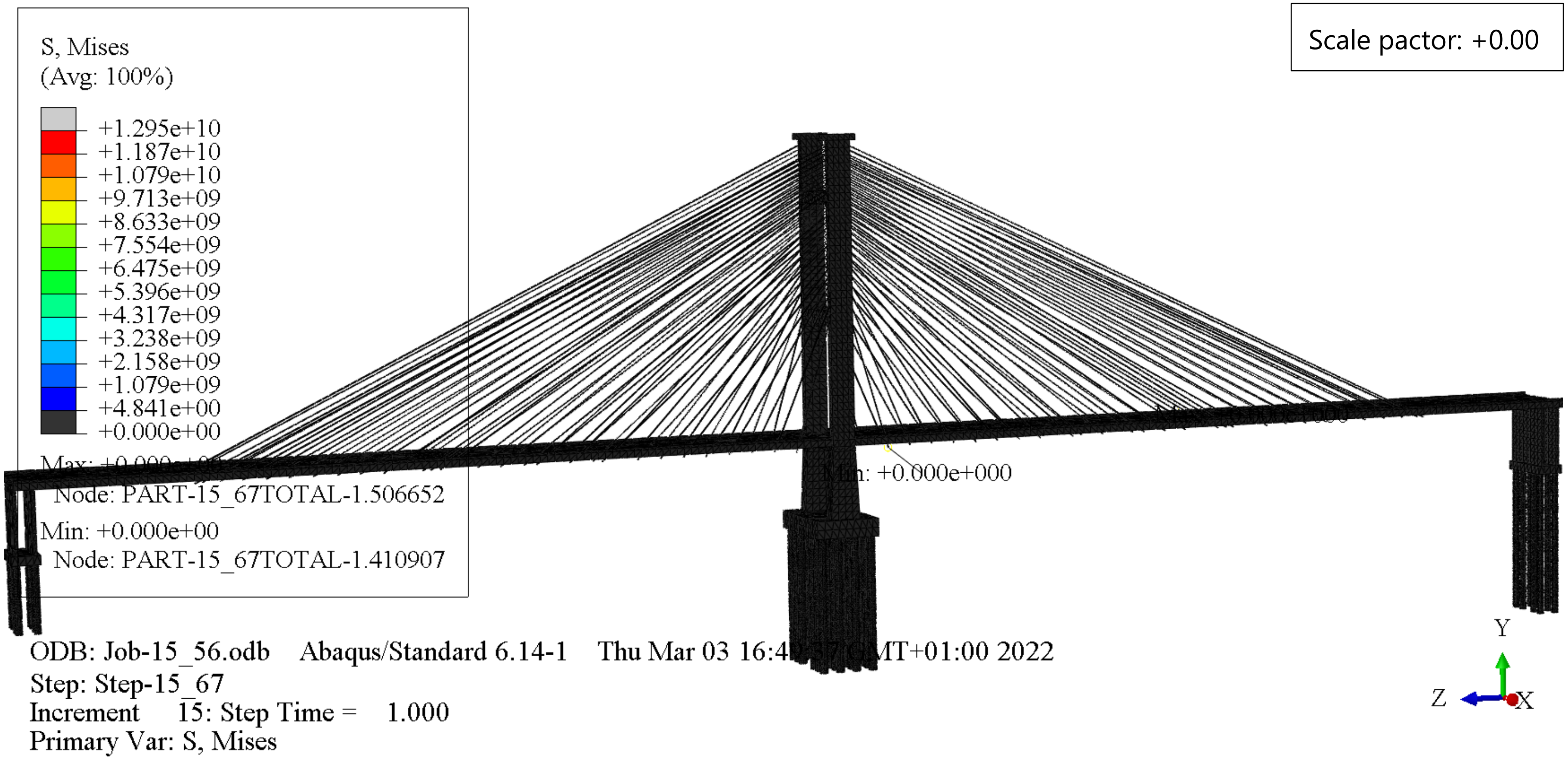
	X_l^a	Local employment data(day).
	X_g^a	Gender discrimination data (day).
	X_s^a	Workers Safety data (day).
	X_S^a	Fair Salary data (day).
	X_L^a	Economic development data (day).
	X_a^m	Accessibility data (day).
	X_u^m	User's safety data (day).
	X_p^m	Public opinion data (day).
Eq.3.14	S_S^3	SIA impact data at the material stage.
	M_S	The impact at the material preparation stage.
	λ_j	The influence probability of uncertain factors (%).
	λ_α	The influence probability of uncertain factors (%-iteration one).
	D_S	The impact of design stage (iteration one).
	C_S	The impact of design stage (iteration two).
	λ_β	The influence probability of uncertain factors (%-iteration two).
	U_S	The impact of design stage (iteration three).
	λ_η	The influence probability of uncertain factors (%-iteration three).
	D_s	The impact of design stage (iteration four).
	λ_ε	The influence probability of uncertain factors (%-iteration four).
Eq.3.15	y_υ	The regression coefficient b_i.
	C_i	The measure of sensitivity.
	$\hat{s}_\iota$	The estimated standard deviation of x_i and y.
Eq.4.1	$\dot{x}$	Variable.
	R^r; R^n	Variable set; the terminal set.
	x; u	The function argument.
	U	The resource set.
	Ω_1	The terminal set.
Eq.4.2	$f^0(x,u)$	Function.
	J	The biggest optimization value.
Eq.4.3	$\dot{Y}$	Variable set.
	M_1	The control variable.
	$\dot{Y}_j$	Variable set of multiple constraints.
Eq.4.4	u	The displacement vector.

	K	The stiffness matrix.
	f	The load vector.
	K_i	The element stiffness matrix of element i.
	n	The total number of finite elements.
	ρ	The vector of design variables.
	$\rho_i^L; \rho_i^u$	The lower and upper limits of design variables.
	$V(\rho)$	The volume under the design variables.
	V_0	Ordiary volume.
	β	The sensitivity constraint.
Eq.4.5	$\sum_{T_1=S}^{T_n=F} F_n(x,y)$	The total data impact of a level in the whole cycle of planning.
	$F_n(x_n, y_n)$	The influence function in the period with x and y as parameters.
	$\min_{x_n,y_n} F_n(x,y)$	The minimum paradigm influence Eq after n times of optimization.
	$x; y$	The vectors corresponding to the factor variable.
	$R^m; k^p$	Sets respectively.
Eq.4.6	$\frac{\sigma W_n}{\sigma S_n}$	The sensitivity value.
	$\max_{F_n} \bigcup_{x_n}^{y_n} S_n$	The maximum weight of the data set affecting sensitivity in each stage.
	$\sum_{T_1}^{T_n}(S_1+,\cdots,+S_n)$	The set of sensitivity impact weights in each stage.
Eq.4.7	$\frac{\sigma w_n}{\sigma s_n}$	Weight final evaluation index.
	F_x^y	Sensitive multi-level planning index parameters.
Eq.4.8	SI	The statically indeterminate structure.
	S_T	The total mass of the framework structure of the bridge.
	n	The number of components.
	l_Y	The longitudinal homogenization length of the bridge (m).
	ρ_Y	The homogenization density of the bridge.
	A_Y	The homogenized section area (m^2).
	$\overline{K}_c; \overline{K}_d$	The optimal torsional and bending stiffness.
	$K_c; K_d$	The mean torsional and bending stiffness.
	K_{max}	The maximum torsional.
	E_e	The elastic modulus of various materials.
	δ_n	The average sensitivity after multiple iterations.

Eq.4.9	ň	The number of finite elements (design domain Ω).
	V_Ω	The volume of the design domain.
	f_o	The allowed volume of structural materials.
	V_e	The finite element volume.
Eq.4.10	ρ_{min}	The lower limit of design variable.
	f_{obj}	The overall objective function of the structure.
	R_{min}	The size of the filtering.
	$\bar{\rho}_e$	The filtered design variable.
Eq.4.11	γ_{im} ; γ_{ln}	The unit grid gravity under different loads (KN).
	S	The total gravity of structure (KN).
	$\left(\sigma^{V}_{i\alpha,\cdots,l\,\beta,\cdots,k(\alpha,\cdots,\beta)}\right)^k$	The Von Mises stress generated by the structure. under the action of k groups of loads ($\mathrm{Kp_a}$).
	$\alpha^i \bigcap \alpha^l, \cdots, \bigcap \alpha^{n,\cdots,m}$	The maximum Von Mises stress controlled by the structure under k groups of loads ($\mathrm{Kp_a}$).
	x_z	The effective element retained under load.
Eq.4.12	$[R]^k$	The elastic modulus matrix.
	$[G]^k$	The geometric modulus matrix.
	$[d]^k$	The product of displacement matrix.
	$[D]^k$	The energy matrix.
Eq.4.13	$x_{ń}$	The influencing factor variable.
	f	h objective function vectors.
	g_i; h_i	Equality constraints.
	$x'_1, \cdots, x'_m$	The multi-level impact data of x_1.
	$\overline{e_1}$	The weight factor of x'_1.
	$\overline{e_m}$; $\overline{e_p}$	The weight factors of x'_m and x'_p.
Eq.4.14	f^e_d	The event frequency.
	p_d	The upgrade probability.
	f_p	The event triggering the upgrade.
	f^e_s	The frequency of overall secondary time.
	f^e_p	The frequency of secondary time.
	P^i_d	The i-level secondary probability.
	J^k_m	A vector.
	k	The index of m group combination of secondary level.
	$\delta(i, J^k_m)$	A function variable.
Eq.4.15	a_j	The weight of the j-level indicator.
	v_j	The information weight of the j-level indicator.

	s_j	The entropy value of the j-level indicator output.
	c_{ik}	The k-level frequency in the i-level evaluation unit.
	$\max\limits_{1\le i\le s}(c_{ik})$; $\min\limits_{1\le i\le s}(c_{ik})$	The maximum and minimum k-level frequency in the evaluation unit.
Eq.4.16	$P_d^{k,m}$	The k; m-level secondary probability.
Eq.5.1	M_f^i	The case assessment standard conclusion.
	$E_1, \cdots, E_{\tilde{a}}$	The assessment indicators (items).
	$\lambda_1, \cdots, \lambda_{\tilde{o}}$	The evaluation coefficients of the indicators.
	$\tau_s^1, \cdots, \tau_s^t$	The sensitivity coefficient (%).
Eq.5.2	$\tau_s^{\bar{a}}$	The average sensitivity coefficient;
	$\min\limits_{1\le i\le \tilde{a}} \tau_s^t$	The minimum sensitivity coefficient.
	$\max\limits_{1\le i\le \tilde{a}} \tau_s^t$	The maximum sensitivity coefficient.

Sources: Own elaboration.



Additional datas Figure 1. Finite element model coupling dynamic time history analysis of JMB (+0.00 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

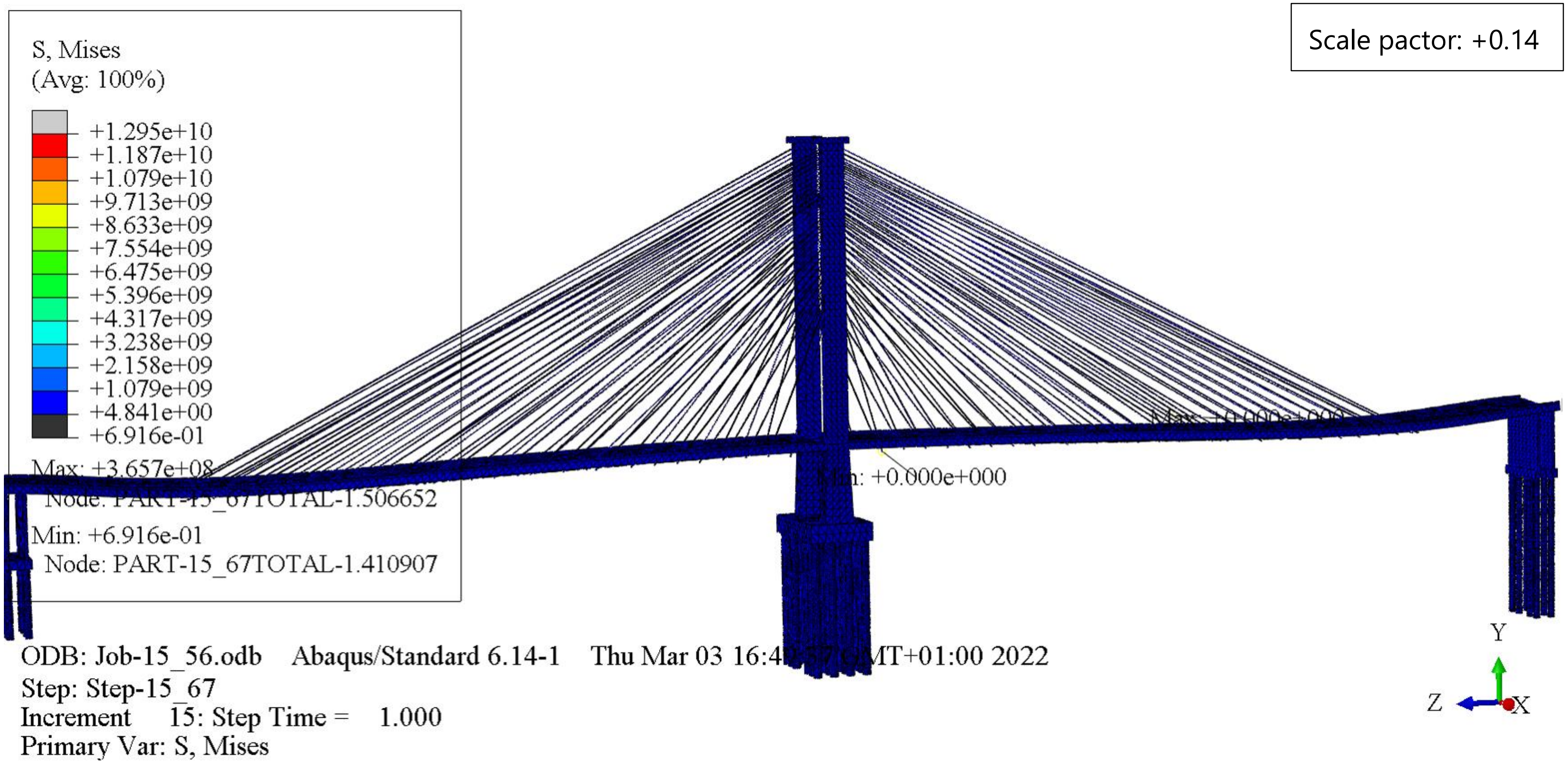


Figure 2. Finite element model coupling dynamic time history analysis of JMB (+0.14 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

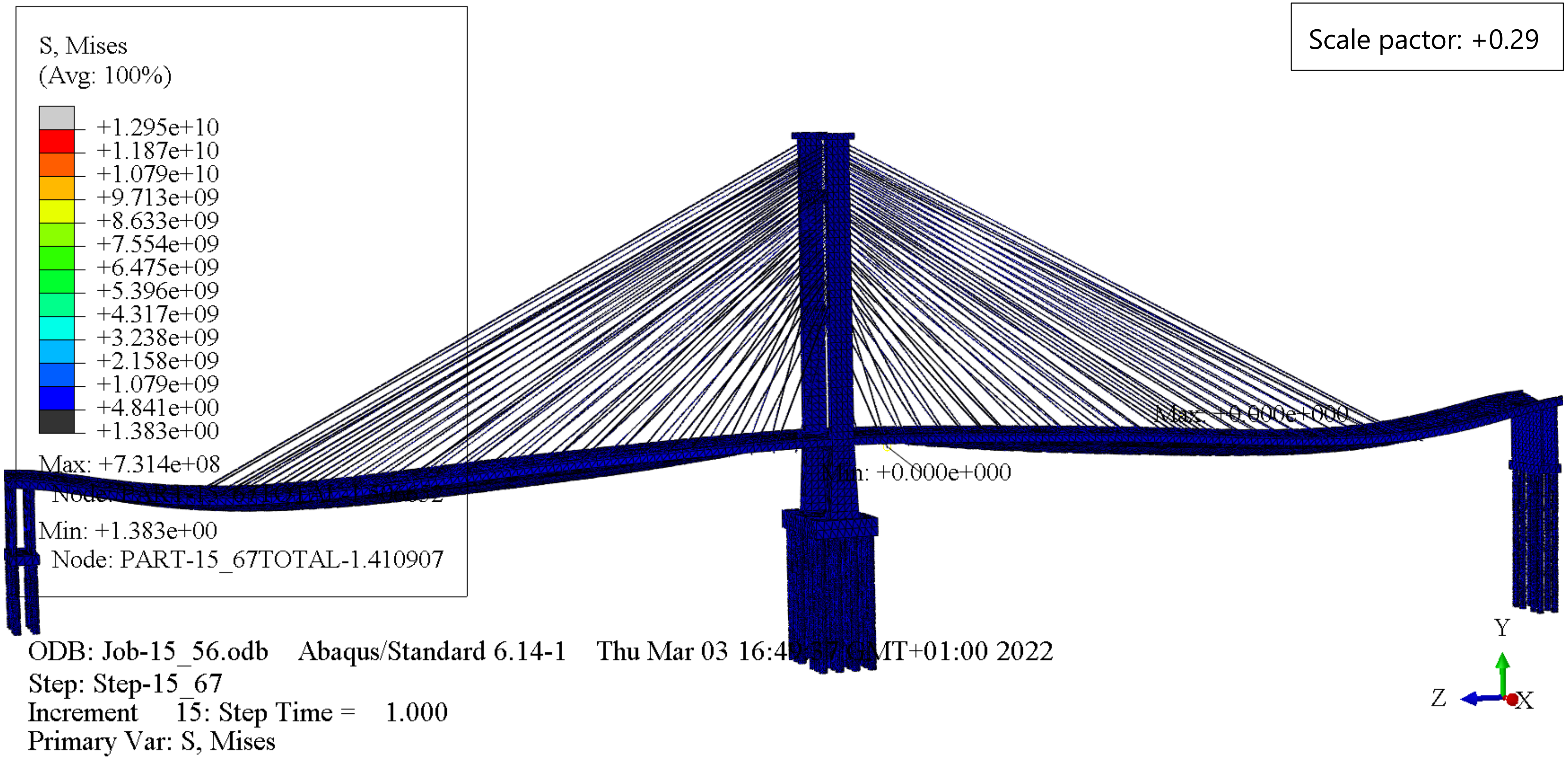


Figure 3. Finite element model coupling dynamic time history analysis of JMB (+0.29 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

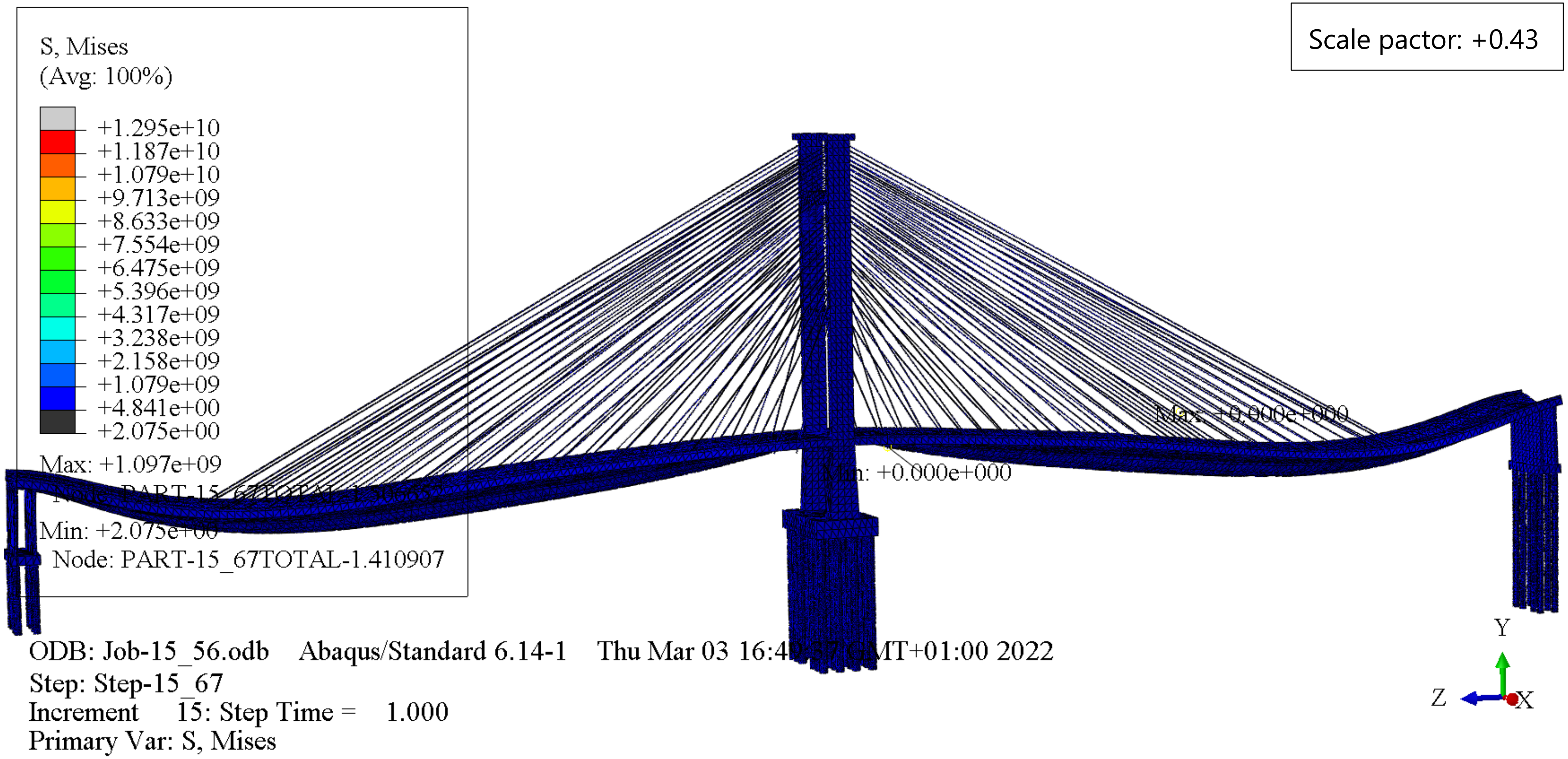


Figure 4. Finite element model coupling dynamic time history analysis of JMB (+0.43 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

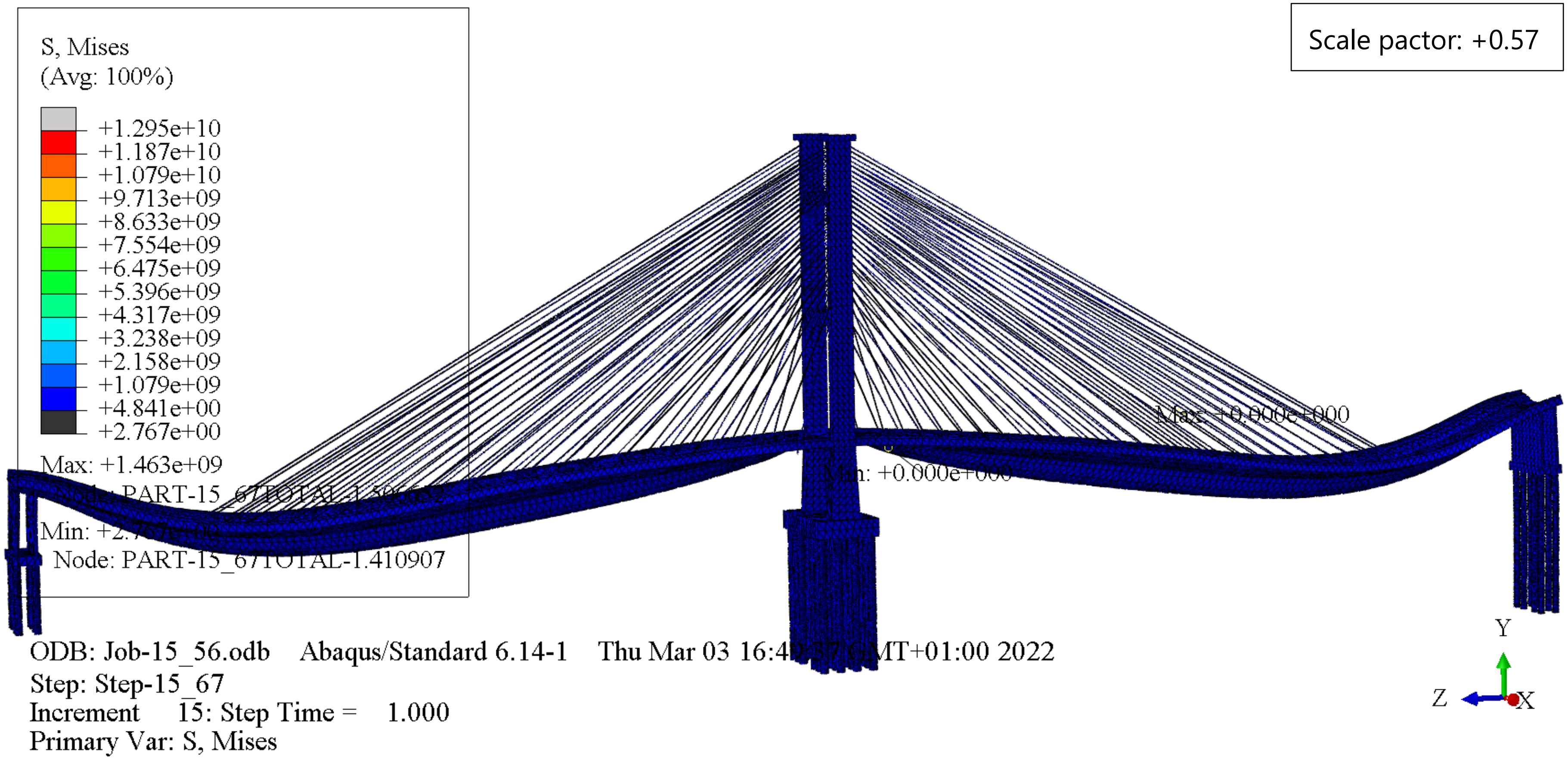


Figure 5. Finite element model coupling dynamic time history analysis of JMB (+0.57 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

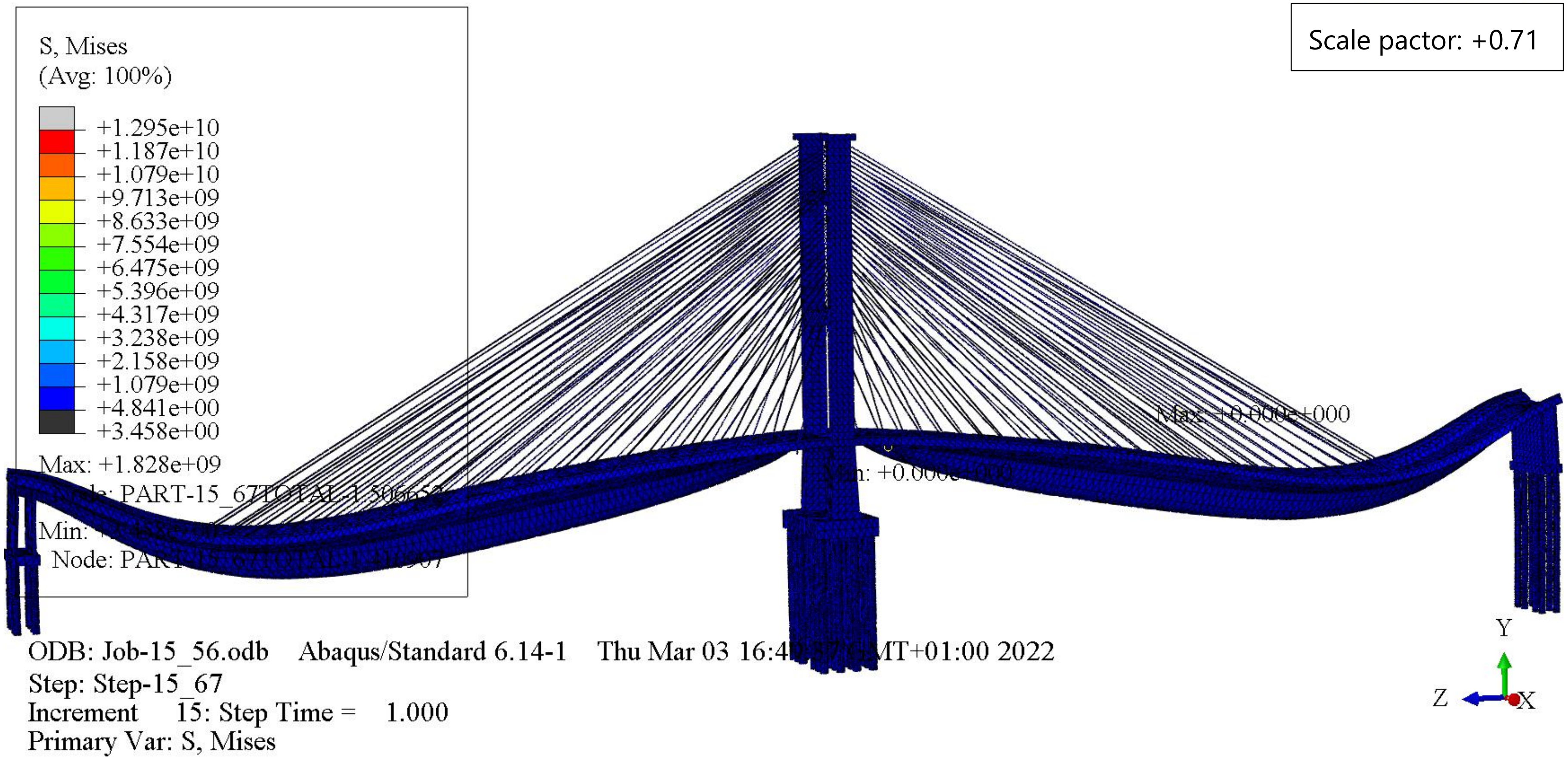


Figure 6. Finite element model coupling dynamic time history analysis of JMB (+0.71 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

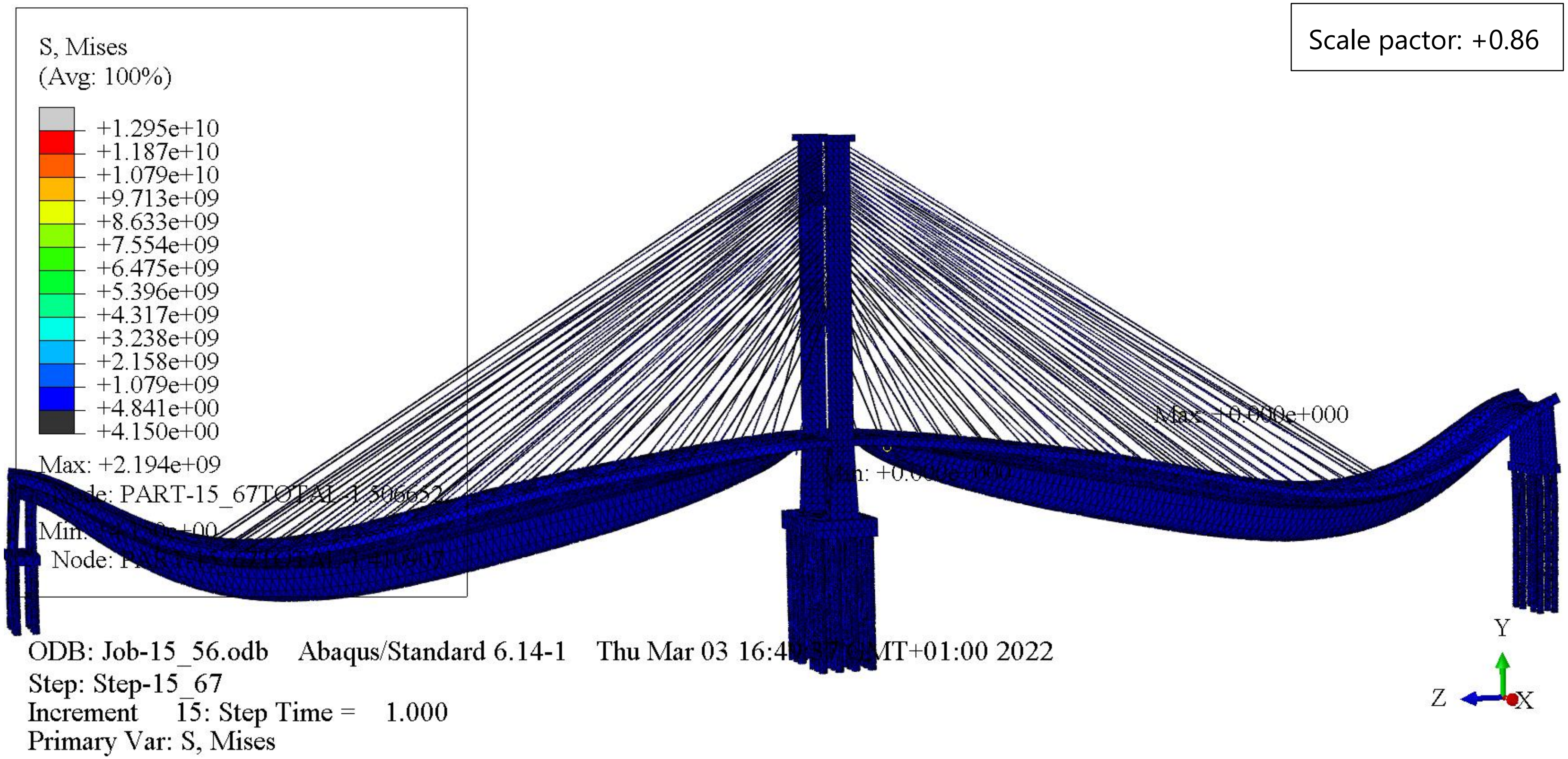


Figure 7. Finite element model coupling dynamic time history analysis of JMB (+0.86 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

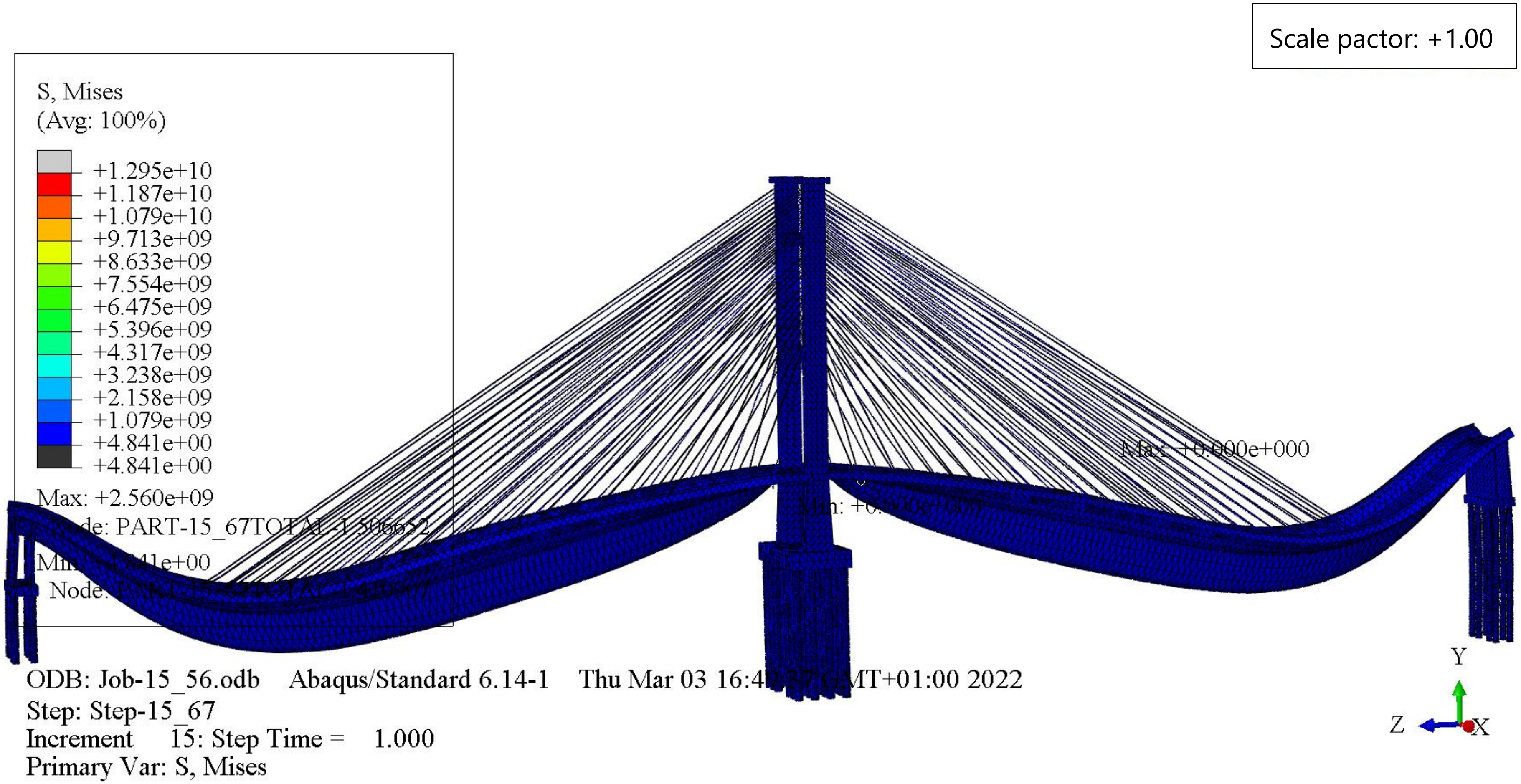


Figure 8. Finite element model coupling dynamic time history analysis of JMB (+1.00 S).

Sources: Own elaboration, and anaiysis used the Abaqus software.

Additional data Figures 1. ~ 8. show the dynamic change time history of mises stress of JMB under external load. It takes one second in total and is completed in eight stages. Adjust the value ratio to 1:8 according to the distribution of the finite element coupling process to clearly observe the dynamic change law of each group of components.

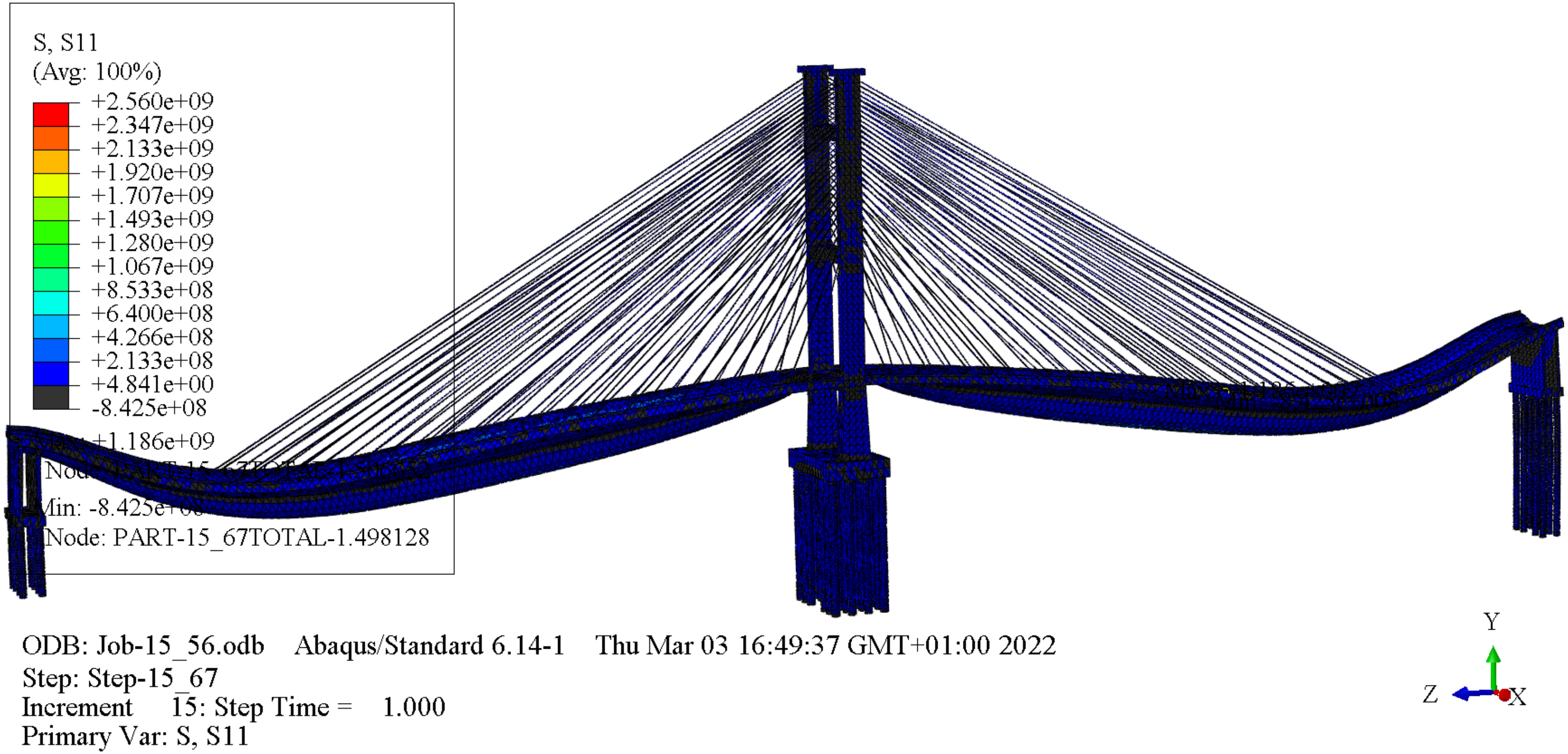


Figure 9. Finite element model coupling analysis of JMB's Mises (S11~ x direction).

Sources: Own elaboration, and anaiysis used the Abaqus software.

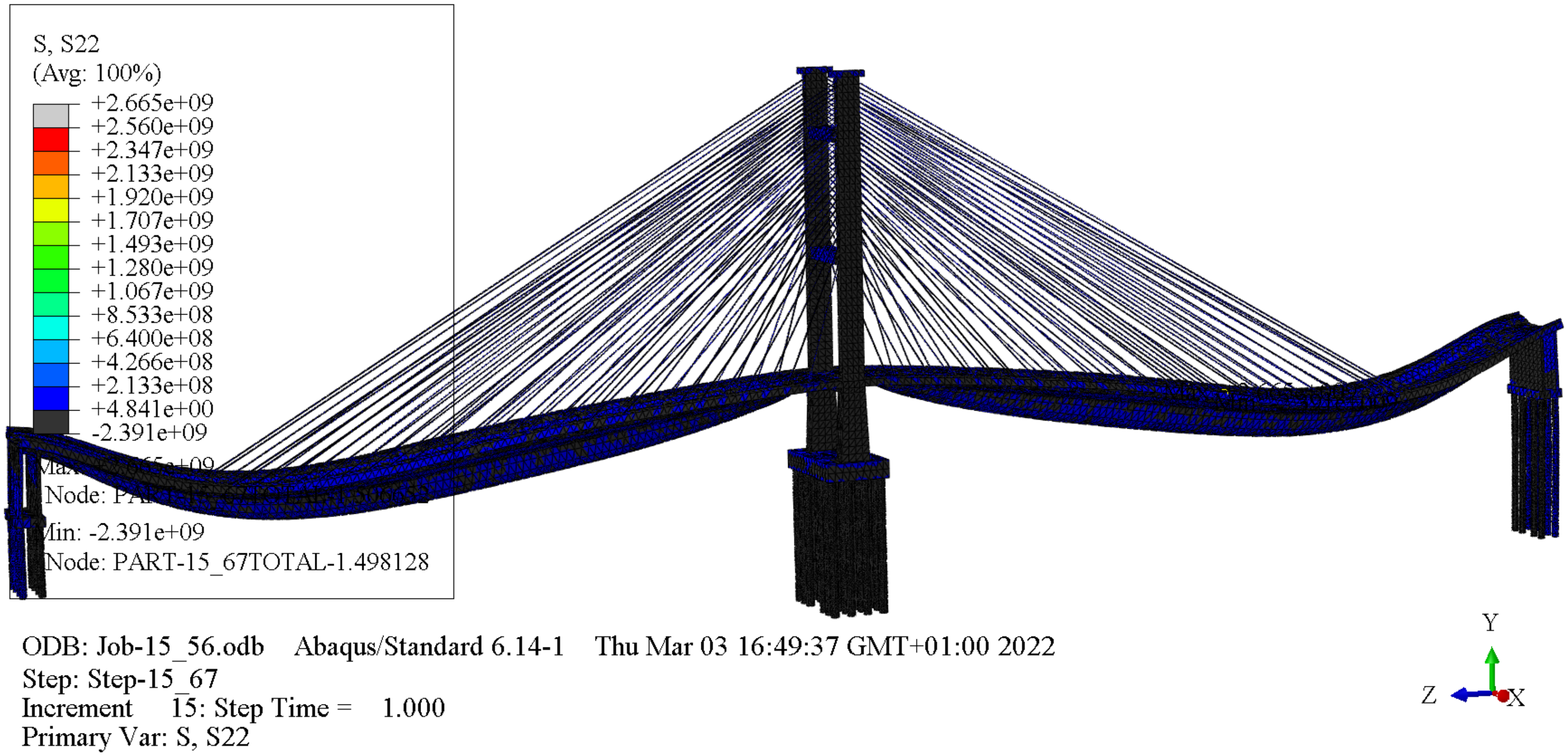


Figure 10. Finite element model coupling analysis of JMB' s Mises (S22~ y direction).

Sources: Own elaboration, and anaiysis used the Abaqus software.

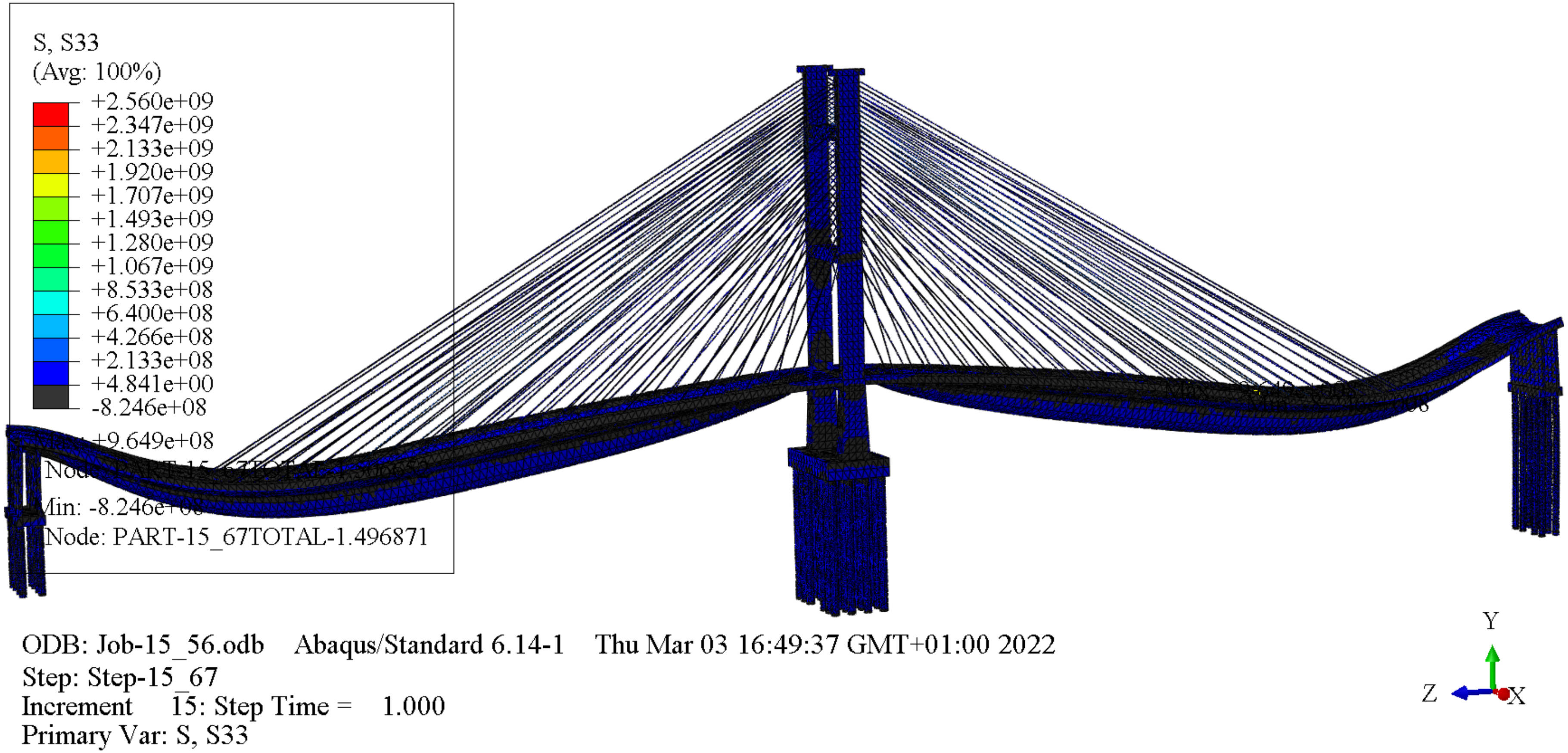


Figure 11. Finite element model coupling analysis of JMB' s Mises (S33~ z direction).

Sources: Own elaboration, and anaiysis used the Abaqus software.

Figures 9.~11. shows the distribution of Mises stress in triaxial direction after JMB completed the finite element coupling analysis.

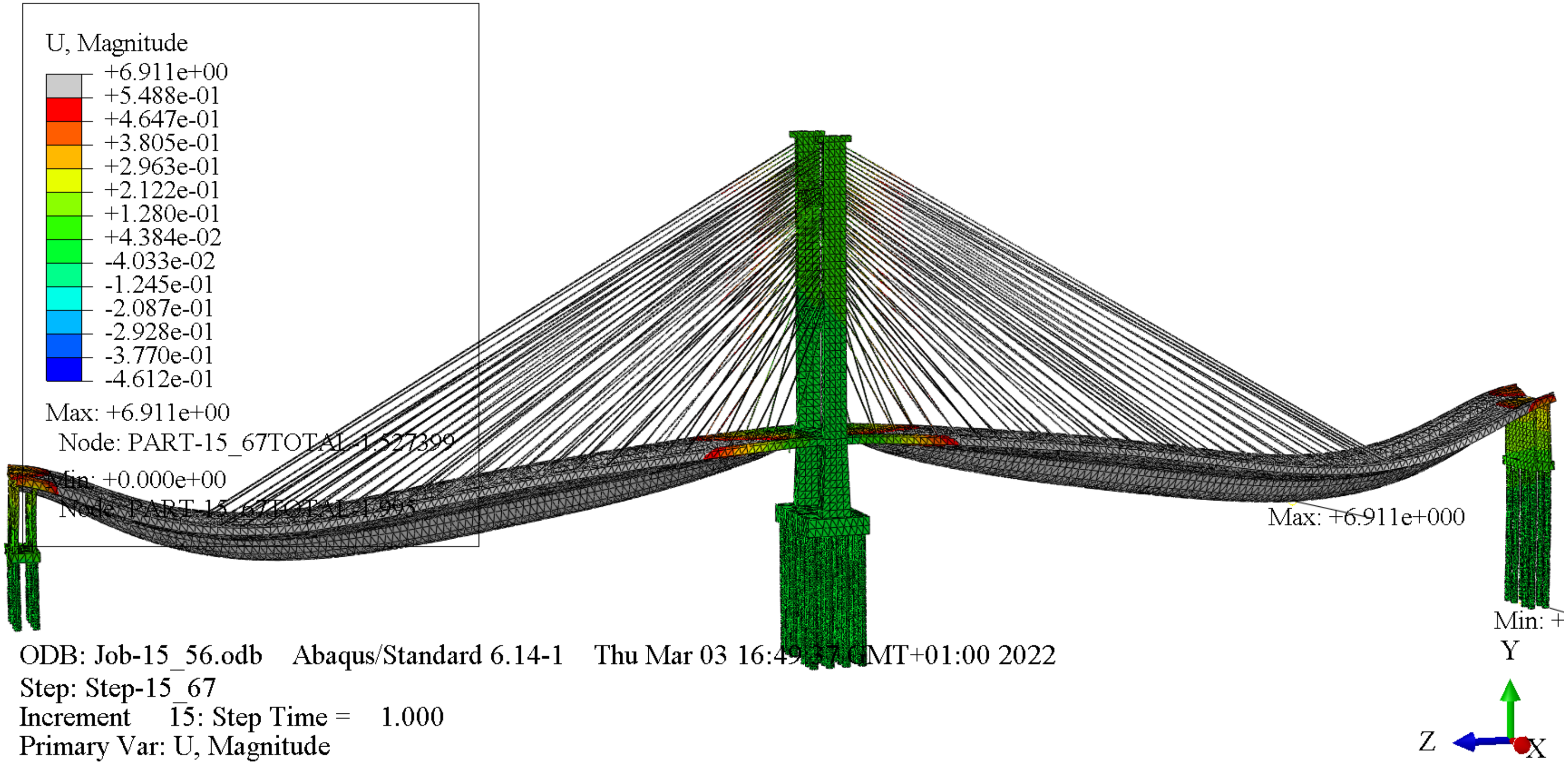


Figure 12. Finite element model coupling analysis of JMB' s displacement (Magnitude).

Sources: Own elaboration, and anaiysis used the Abaqus software.

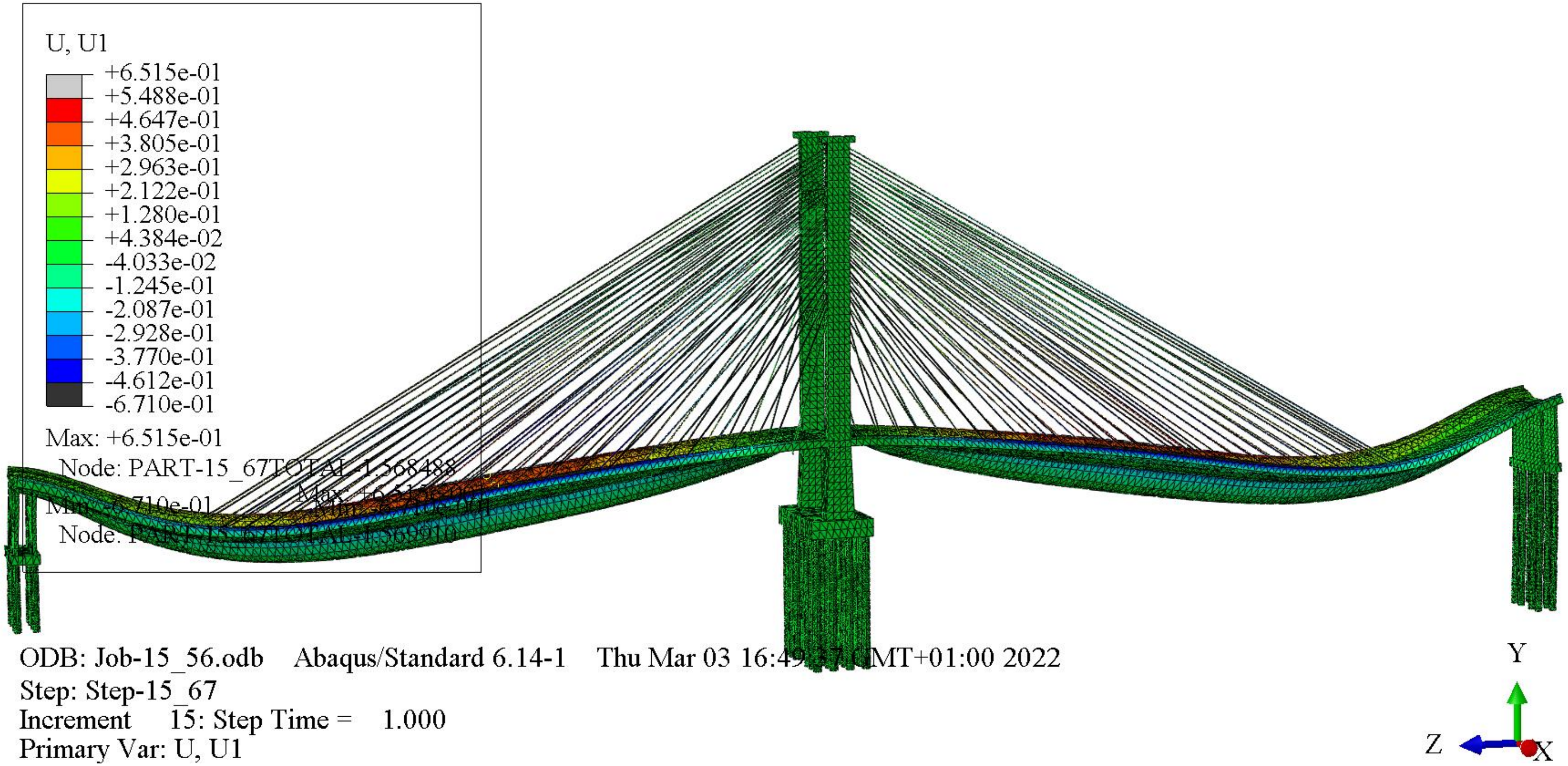


Figure 13. Finite element model coupling analysis of JMB' s displacement (U11~ x direction).

Sources: Own elaboration, and anaiysis used the Abaqus software.

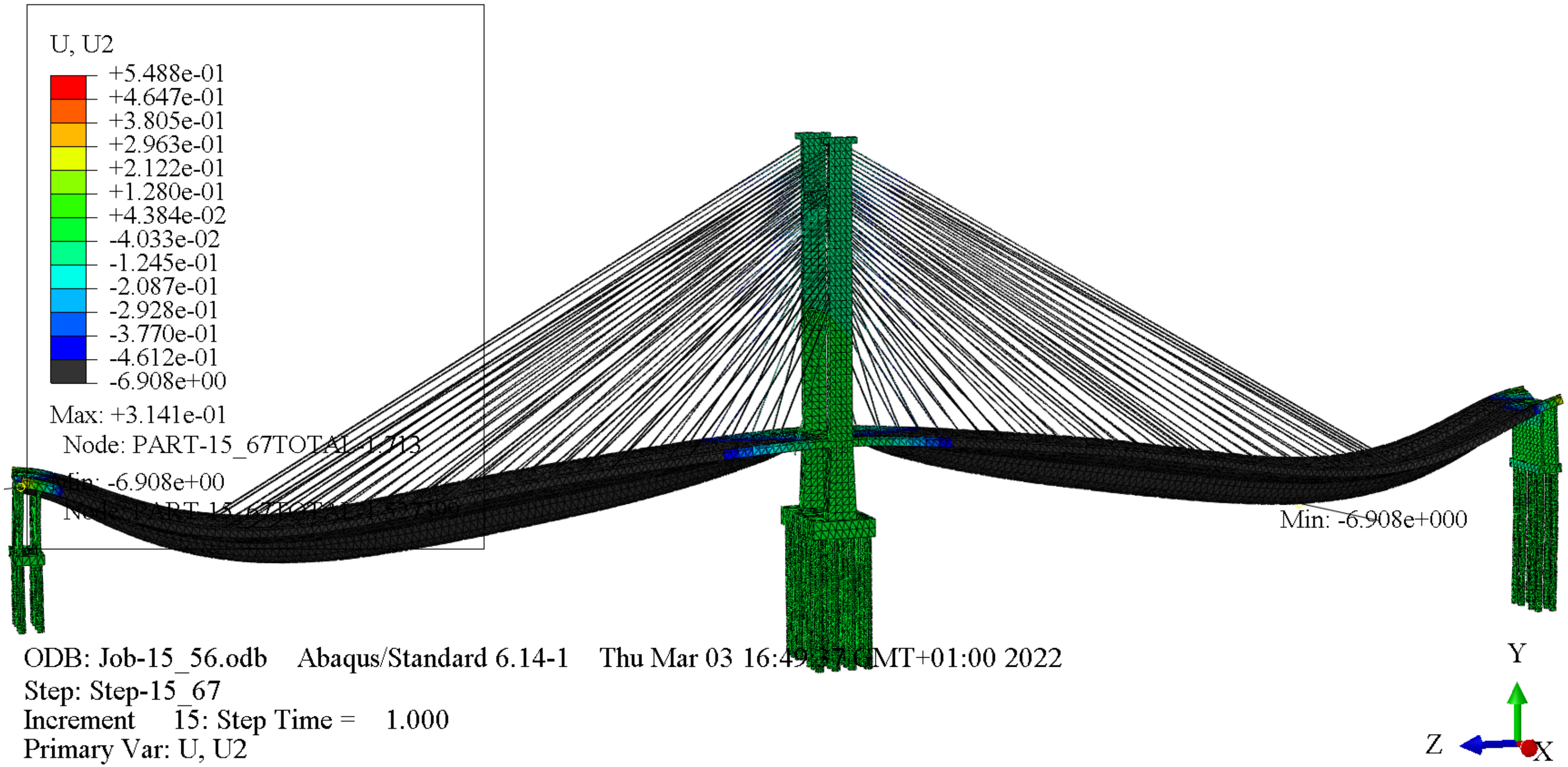


Figure 14. Finite element model coupling analysis of JMB' s displacement (U22~ y direction).

Sources: Own elaboration, and anaiysis used the Abaqus software.

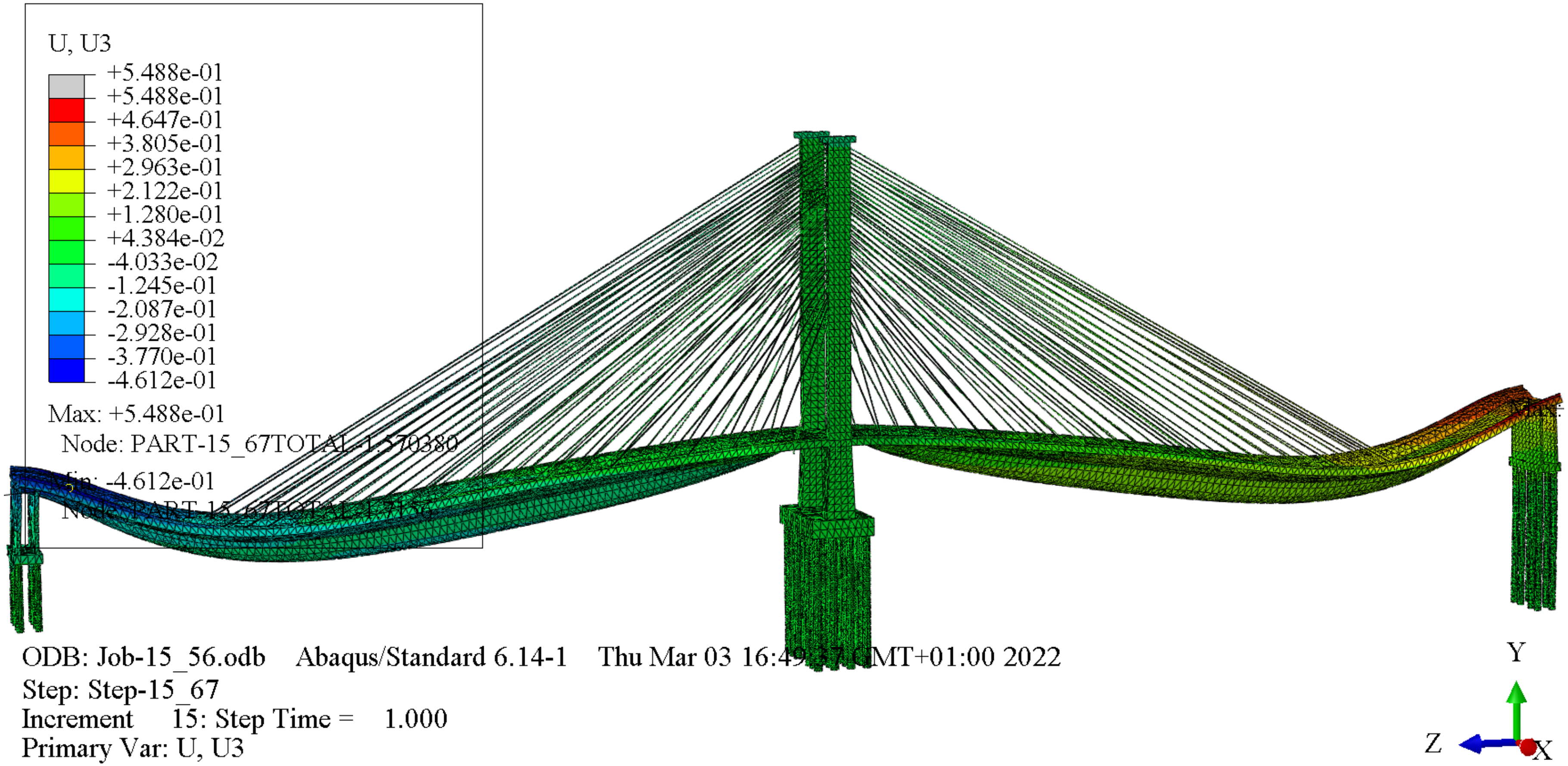


Figure 15. Finite element model coupling analysis of JMB' s displacement (U33~ z direction).

Sources: Own elaboration, and anaiysis used the Abaqus software.

Figures 12.~15. Show the total displacement of JMB under extreme load and the displacement change vector in the x, y, and z directions. Under different stress distributions, the displacement is rearranged.