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EXPLORING THE IMPACT OF MULTIDIMENSIONAL COMPLEXITY INTERPLAY ON THE SUCCESS OF MEGA INFRASTRUCTURE PROJECTS

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Abstract. Complexity is an inherent characteristic of mega infrastructure projects (MIPs), playing a crucial role in determining their success. While existing research has explored the effects of individual complexity factors, the interplay of multidimensional complexities and their collective impact on MIP success remains underexamined. This study systematically identifies complexity factors from both internal and external dimensions, leveraging the TOE framework and grounded theory, and empirically investigates their dynamic interactions. Seven key complexity factors are identified and hypotheses regarding their interplay and influence on the success of MIP are proposed and tested using structural equation modeling (SEM). The findings reveal that external complexity amplifies the effect of internal complexity on the success of MIPs. Furthermore, internal complexity factors exhibit substantial interaction effect, with the latter exerting a stronger impact compared to the former. Collectively, complexity factors demonstrate a negative impact on the success of MIPs. This research advances the understanding of MIP complexity by examining the dynamic interaction among multidimensional complexity factors. It also provides practical insights for project managers to effectively identify and manage critical internal and external complexity drivers, thereby improving the likelihood of success for MIPs.

Keywords: mega infrastructure projects (MIPs), complexity, project success, grounded theory, structural equation modeling.

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Notations

Abbreviations

MIPs – Mega Infrastructure Projects;
TEC – Technological complexity;
ORG – Organizational complexity;
TAS – Task complexity;
EE – Ecological environmental complexity;
TE – Technological environmental complexity;
ME – Market environment complexity;
SE – Social environmental complexity;
PS – Project success.

1. Introduction

Mega Infrastructure Projects (MIPs) are large-scale public works that play a crucial role in ensuring the fundamental stability and well-being of various industries and public life (Chen et al., 2015). These projects cover various sectors, such as transportation infrastructure (highways, railways, airports), utilities (water supply, sewage systems, electrical grids), large public buildings (schools, hospitals) and communication systems. MIPs exert a profound influence on the politics, economy, society and environment of a country or region (Flyvbjerg et al., 2009; Sanderson, 2012). Due to their extensive scale, long-term planning, heterogeneous stakeholder engagement, interdisciplinary collaboration, substantial investment and fi-

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nancing, MIPs exhibit a higher level of complexity than conventional construction projects. They often lead to difficulties in successful delivery (Wang & Yuan, 2017; Lin et al., 2023). Scholars contend that the inefficient or failure of numerous MIPs can be attributed to inadequate management of their complexity (Mirza & Ehsan, 2017; Bhangale et al., 2025). Consequently, effectively managing the complexity of MIPs is critical for project managers and a decisive determinant of project success. The failure of MIPs not only hinders infrastructure development but also adversely impacts project financing, public welfare, and socio-economic progress (Park, 2021). A critical factor contributing to such failures is financial mismanagement. Empirical evidence suggests that a staggering 90% of MIPs experience cost overruns, with over half exceeding their budgets by 50% or more – a recurring issue that significantly undermines project viability (Flyvbjerg, 2014). Hence, only through systematic identification and management of complexity during both construction and operational phases can MIPs avoid the stigma of failure.

Scholars from different theoretical frameworks and research perspectives have offered explanations on the concept of complexity (Baccarini, 1996; Tatikonda & Rosenthal, 2000; Dao et al., 2017). However, a consensus on a unified understanding of complexity has yet to be reached. From the perspective of systems theory, the complexity of MIPs refers to the complexity of the interrelated elements and subsystems of MIPs; while from the perspective of engineering practice, the complexity is defined as the conflicting technical, resource, time and other factors faced by project participants throughout the life cycle of the project (Damayanti et al., 2021a). Many scholars have operationalized the concept of complexity by identifying specific attributes, known as complexity factors, that can be directly observed and managed by project managers (Mirza & Ehsan, 2017; Odusanya et al., 2021; Sruthilaya et al., 2025). In summary, this study defines complexity as a measure that can indirectly measure the degree of complexity involved in a MIPs project or system.

The Technical, Organizational, and Environmental (TOE) framework provides a valuable theoretical lens for identifying complexity factors in MIPs, having been successfully applied in prior studies of large-scale engineering systems (He et al., 2015; Ma & Fu, 2020). However, both the specific constituent elements of these complexity factors in the MIP context and their complex interrelationships still require further exploration. Project complexity is widely acknowledged as a key influencing factor that can negatively impact the outcomes of projects (Tatikonda & Rosenthal, 2000). Researchers have examined the effects of project complexity on project success, revealing that goal complexity and stakeholder's engagement have significant impact on project outcomes (Floricel et al., 2016; Luo et al., 2017; Nguyen et al., 2021). Complexity factors can lead to problems and changes in the project system, which can then trigger the emergence of additional complexities and potential correlations among them (Maylor et al., 2008). Although existing literature has established the fundamental relationship between complexity and project success (Tatikonda & Rosenthal, 2000; Brady & Davies, 2014), the compounding effects resulting from the interactions between different complexity factors in Mega Infrastructure Projects (MIPs) remain poorly understood (Xue et al., 2020).

This study aims to develop a theoretical model that explores examining the dynamic interactions among complexity factors in Mega Infrastructure Projects (MIPs) and their collective influence on project success. The research objectives include: 1) identifying the complexity factors through the combination of TOE framework and grounded theory; 2) proposing hypotheses of the interplay between the multidimensional complexity and its impact on the success of MIPs; 3) empirical testing the hypothesis model and identifying key complexity factors and pathways. By adopting an interaction-centric perspective, this research contributes to both theoretical understanding and practical management of MIP complexity, offering evidence-based strategies for mitigating complexity through targeted interventions in key internal and external complexity dimensions, ultimately improving the likelihood of project success.

2. Literature review

2.1. TOE framework for complexity of MIPs

The TOE framework provides a comprehensive approach to analyze and understand complexity factors inherent in large engineering projects (Bosch-Rekveldt et al., 2011). It categorized complexity into three dimensions: technical, organizational and environmental. The summary of the existing research is presented in Table 1.

Technical complexity in engineering projects encompass factors such as technical diversity, technical uniqueness, technical interdependence, technical novelty, interdependency among construction activities, and the inherent complexity of engineering technology itself (Wood & Ashton, 2010; Nguyen et al., 2015; Ma & Fu, 2020). The application of advanced technological systems, new materials and construction processes has further heightened technical complexity of MIPs (Wood & Ashton, 2010; He et al., 2015). Within the TOE framework, project goals and scopes are deeded as technical complexities of a mega-project, which are also categorized as structural complexity (Williams, 1996; Geraldi et al., 2011). Nevertheless, a clear consensus definition of technical complexity in MIPs is currently lacking, as well as a systematic identification of its subcategories.

MIPs consist of multiple teams from different organizations, creating a loosely coupled large-scale multi-subgroup network with complex, interdependent task structures and intricate contractual relationships. Each team has its own internal organization structure and a diverse range of knowledge and skills. Organizational complexity is reflected in aspects such as interorganizational relationships, decision-making authority, and task allocation with-

Table 1. The summary of the literature

No	Complexity Dimensions	Research Methods	Key Findings	References
1	Technical, Organizational and Environmental complexity	Literature review and empirical research	Develop a TOE framework for large-scale project complexity.	Bosch-Rekveldt et al. (2011)
2	Structural, uncertainty, dynamism, pace, and sociopolitical complexity	Literature review	Propose a five-dimensional complexity framework.	Geraldi et al. (2011)
3	Technological, organizational, goal, environmental, cultural, and information complexity	Literature review and two-round Delphi survey	Develop a complexity measurement model using FANP (Fuzzy Analytic Network Process).	He et al. (2015)
4	Technological, organizational, goal, environmental, cultural, and information complexity	Qualitative Comparative Analysis (QCA)	Identified mechanisms of complexity's impact on mega-project success: High organizational/environmental complexity leads to delays. High technical/target complexity leads to cost overruns. High technical/environmental complexity + low organization leads to poor quality.	Ma and Fu (2020)
5	Sociopolitical, environmental, organizational, infrastructural, technological, and scope complexity	Fuzzy Analytic Hierarchy Process (Fuzzy AHP)	Sociopolitical complexity is the most critical dimension in transportation projects.	Nguyen et al. (2015)
6	Institutional complexity	Case study and multi-level analysis	Environmental factors affect institutional complexity.	Qiu et al. (2019)
7	Inherent, uncertainty, technological quantity, phase overlap, organizational inherent complexity	Expert interviews and questionnaire survey	Develop a complexity factor checklist for Construction projects.	Wood and Ashton (2010)
8	Architectural structure/function, construction methods, schedule urgency, scale, geology, and adjacent environment	Three-round Delphi survey	Identified six key complexity metrics.	Xia and Chan (2012)
9	Environmental complexity	Fraud triangle theory and fuzzy-set Qualitative Comparative Analysis (fsQCA)	Study finds that economic, institutional and information factors affect the environmental complexity of megaprojects.	Xie et al. (2023)
10	Task complexity and organizational complexity	Case study and ProjectSim simulation model	Task complexity and organizational complexity affect project success by increasing hidden workloads.	Lu et al. (2015)
11	Information, task, technological, organizational, environmental, and goal complexity	Literature review and Structural Equation Modeling (SEM)	Information and goal complexity significantly reduce project success.	Luo et al. (2017)
12	Organizational complexity	Case study	External environmental changes drive organizational evolution.	Wang et al. (2023)
13	Technical, organizational, and institutional complexity	Case study and semi-structured regression analysis	Technical and organizational complexity harm performance.	Floricel et al. (2016)
14	Stakeholder engagement (SE)	Literature review and SEM	Stakeholder engagement negatively affects complex project performance.	Nguyen et al. (2021)
15	Structural and dynamic complexity	Comparative case study	Structural/dynamic complexity jointly influence success.	Brady and Davies (2014)

in MIPs (Qiu et al., 2019; Denicol et al., 2021; Wang et al., 2023; Castelblanco et al., 2024). Despite being considered a fundamental aspect of project complexity, existing literature has not systematically identified its subcategories (He et al., 2015).

Environmental complexity refers to the intricacies of the natural environment at the project site and the complexities of the social factors involved in the operation of a megaproject (He et al., 2015). This includes factors such as topography, climate, natural elements of the project site, as well as socio-political, economic, and regulatory factors (Xia & Chan, 2012; Ma & Fu, 2020). Scholars agree that the environment plays a pivotal role in determining the complexity of MIPs, given their extensive scope, long duration, and high vulnerability to the natural environment (Ma & Fu, 2020; Xie et al., 2023). The construction of MIPs requires significant resources and often garners substantial influence from social and contextual dynamics. While existing studies have incorporated both natural and social factors into the assessment of environmental complexity, there is a dearth of research specifically focused on categorizing environmental complexity in MIPs.

As a result, it has become apparent that the TOE framework has certain limitations for complexity analysis in MIPs. The TOE framework classifies complexity in MIPs broadly, and environmental complexity accounts for an increasing proportion of MIPs as globalized carbon-reduction policies are pursued. Accordingly, this study employs the grounded theory research method to expand the TOE framework with the aim of developing a comprehensive framework that can effectively measure and assess complexity in MIPs. By addressing the gaps in the existing framework, this research aims to provide a more robust and practical tool for understanding and managing complexity in the context of MIPs.

2.2. Success of MIPs

The achievement of quality, cost, and schedule goals is no longer sufficient evidence of the project's success (Wong & Cheung, 2005; Lam et al., 2011). As Sun and Zhang (2011) cogently argue, megaproject success must be fundamentally redefined to prioritize stakeholder satisfaction, particularly in meeting owner expectations, which emerges as the paramount success criterion that transcends conventional performance metrics. Similarly, Luo et al. (2017) suggested that the criteria for project success should include owner satisfaction. Shenhar and Holzmann (2017) indicated that the success of MIPs included the comprehensive impact of their entire life cycle on aspects of society, economy, and ecology. Other scholars argue that sustainability should serve as the primary indicator of the success of MIPs (Klakegg, 2009; Coskun et al., 2023). Moreover, the success of MIPs has expanded from focusing solely on the construction phase to the operation phase (Ma & Fu, 2020). This study identified five key indicators for measuring the success of MIPs: (1) schedule; (2) quality; (3) cost; (4) satisfaction of project stakeholders; and (5) the value of project operation. Specifically, the latter indicator encompasses sustainability, environmental performance, user satisfaction, and commercial value during the operation of MIPs.

Project complexity is widely acknowledged as a key influencing factor that can negatively impact the outcomes of projects (Tatikonda & Rosenthal, 2000). Researchers have employed various approaches to examine the effects of project complexity on project success. More scholars use structural equation and multiple regression (MR) analyses to study the impact of project complexity on project success. Floricel et al. (2016) showed that technical complexity and organizational complexity negatively affect project performance, whereas institutional complexity positively affects project performance. Luo et al. (2017) argued that informational complexity and goal complexity have a significant negative impact on project success of MIPs. Nguyen et al. (2021) found that stakeholders in complexity projects have a negative impact on project performance. Other scholars used qualitative comparative analysis to study the relationship between complexity and project success in MIPs, Ma and Fu (2020) argued that different combinations between organizational, environmental, goal, and technical complexity negatively affect project success in terms of schedule, cost, and quality. Complexity factors in MIPs generate non-linear interactions that manifest as systemic challenges, subsequently inducing adaptive changes within the project ecosystem (Maylor et al., 2008). This dynamic process frequently precipitates emergent complexities, thereby establishing recursive relationships among various complexity dimensions. While existing research has substantially examined the direct effects of complexity on project performance (Tatikonda & Rosenthal, 2000; Brady & Davies, 2014), the compounding impacts arising from the interdependencies between different complexity factors remain critically understudied, particularly in the context of mega infrastructure projects (Xue et al., 2020).

It has been a research trend in the field of project management to study the impact of correlations between critical success factors on project success in other types of projects. Barbosa et al. (2021) demonstrated through fsQCA analysis that in open innovation projects, combining structured planning with organic communication enhances performance when collaborating with scientific partners, challenging the traditional approach of isolating success factors. Crisan et al. (2023) revealed that in social projects, configurations of external environment, organizational resources, and project strategies collectively determine success outcomes.

In contrast to open innovation projects (OIPs) and multiple social projects (MSPs), MIPs are large in scale, involve a wide range of people, and the overall environment of the project is more complex, so the impact of project complexity on project success is not singular or independent in MIPs. Although existing studies have identified these complexity factors and validated their individual impacts on project success, these studies tend to ignore the interactions and correlations between complexity factors. Therefore, this study fills this research gap by exploring how the interactions between complexity in MIPs collectively affect project success from the perspective of the correlative role of complexity.

3. Research framework and hypotheses

3.1. The proposed complexity framework of MIPs

The identification of complexity in MIPs requires a rigorous and informative approach to theory development. Grounded theory, rooted in extensive data analysis, is typically employed for this purpose. It involves capturing relevant descriptions from the literature and progressively refining generalizations from the bottom up, level by level. Compared to other qualitative analysis methods, grounded theory offers a more comprehensive approach to studying project complexity and capturing emerging factors in real-time, thereby facilitating theory construction (Stol et al., 2016). Notably, grounded theory is not only used to construct new theories, but also to expand the scope of exist-

ing ones (Urquhart et al., 2010). Thus, this study employs grounded theory to identify complexity factors in MIPs based on the TOE framework, thereby extending and enriching the existing framework and presenting a comprehensive understanding of complexity in MIPs. The formulation of research hypotheses and the subsequent research methods are shown in Figure 1.

Based on TOE framework, the grounded theory to identify complexity factors is divided into three steps, collecting information, coding and constructing the MIPs complexity framework. First, collect typical MIPs project cases and relevant literature as well as news report information about the project cases. Second, construct a MIPs case base using the information collected in first step, and then the grounded theory approach is applied in this study to uncover complexity factors in MIPs through a three-phase information encoding process using six case MIPs in China (shown in Appendix). The three phases include open coding, axial coding, and selective coding.

Open coding is the initial step in the processing of the underlying information, where relevant descriptions of complexity factors are captured and transformed into a more standardized language, adapting to the large and more dispersed number of complexity factors through the overlay scanning of MIPs' information. After the open coding was completed, the similar descriptions were further refined to form the main dimensions of the complexity factors, which was the axial coding. The third step of selective coding is the re-degradation of the main four degrees encoded in axial coding, which transforms the main dimensions of complexity factors into core dimensions. Finally, construct the MIPs complexity framework based on the results of the coding.

In this study, an overlay scan method was utilized to comprehensively collect a set of complexity factors from the case MIPs. Reference nodes were collected, e.g., more than 400 new patents in the Hong Kong-Zhuhai-Macao Bridge (HZMB) Project, the overall design and key technologies are all independently developed, and innovative use of technology, workmanship of China-Russia crude oil pipeline project. And these reference nodes are standardized and grouped into open codes technically challenging (a4).

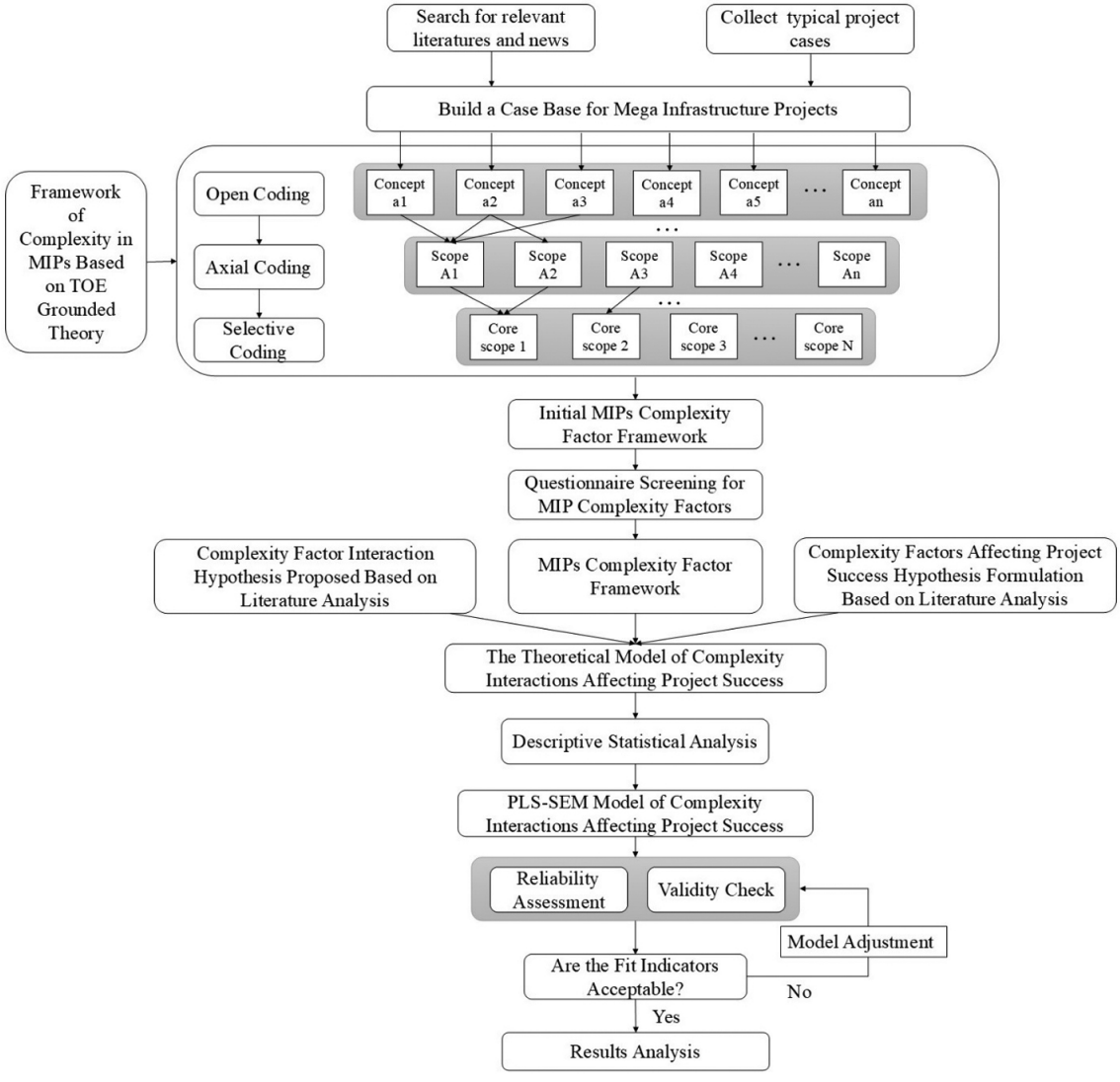


Figure 1. Research hypotheses and the subsequent research methods

Once the initial open coding process is completed, similar descriptions are further refined, classified, and summarized based on their main terms. This process contributes to the identification of the main dimensions of complexity factors and constitutes the axial coding phase. Summarize open coding legitimacy of the use of new technologies, processes, materials and patents (a2), highly demanding and difficult design of structures and materials (a3) and technically challenging (a4) into axial coding for difficulty of technology and application risk (A2). Followed by the selective coding, the main dimensions of the complexity factor are refined and categorized. Nodes in the axial coding with a shared path of action are identified as core nodes, forming the transformed core dimensions of the complexity factor. According to the main dimensions of complexity, further categorization of axial code diversification of technology (A1), difficulty of technology and application risk (A2), convergence of construction processes (A3) and completion of processes (A4) as selective coding Technological complexity (TEC).

The complexity framework of MIPs was developed using grounded theory and encompasses technical complexity, organizational complexity, task complexity, and environmental complexity. Table 2 presents the fundamental framework for axial coding and selective coding. Among these dimensions, technological complexity, organizational complexity, and task complexity are considered internal complexities of MIPs. In studies on project complexity, some scholars have found that environmental complexity affects organisational and institutional complexity, i.e., external complexity affects internal complexity (Qiu et al., 2019; Wang et al., 2023). Other scholars found that economic, institutional, and information factors in internal complexity affect environmental complexity (Xie et al., 2023). Therefore, this article divides complexity into internal complexity and external complexity to explore the influence relationship between internal and external complexity.

Ecological environment complexity, technological environment complexity, market environment complexity,

Table 2. The extracted complexity factors for MIPs based on grounded theory

Axial coding nodes	Selective coding nodes
Diversification of technology (TEC1)	Technological complexity (TEC)
Difficulty of technology and application risk (TEC2)	
Convergence of construction processes (TEC3)	
Completion of processes (TEC4)	
Organizational structure and governance (ORG1)	Organizational complexity (ORG)
Temporal and spatial differentiation of teams (ORG2)	
Dynamism of organizational relationships (ORG3)	
Collaboration and information sharing among teams (ORG4)	
Capability and mobility of managerial staff (ORG5)	
Risk of engineering procurement (ORG6)	
Complexity of contract management (ORG)	
Limitations of quantity and quality of resources (TAS1)	Task complexity (TAS)
Resource allocation and scheduling (TAS2)	
Complexity of capital structure (TAS3)	
Diversification of construction goals (TAS4)	
Relevance and integrity of engineering tasks (TAS5)	
Dynamism of engineering tasks (TAS6)	
Engineering changes and risks (TAS7)	
Harsh construction environment (EE1)	Ecological environmental complexity (EE)
Complexity of ecological environment governance (EE2)	
Incomplete policies, standards, and specifications (TE1)	Technological environmental Complexity (TE)
Diversification of cross-regional technical standards (TE2)	
Differences in cross-regional financing policies (ME1)	Market environment Complexity (ME)
Dynamism of international or domestic markets (ME2)	
Imperfection of legal systems (ME3)	
Diversity of stakeholder demands (SE1)	Social environmental complexity (SE)
Dynamism of stakeholder demands (SE2)	
Stability of international and domestic politics (SE3)	
Differences in cross-regional political environments (SE4)	
Differences in cross-regional cultures (SE5)	
Social attention and impact of the project (SE6)	

and social environment complexity are regarded as external complexity of MIPs. Ecological environment complexity is the increased difficulty in the design, construction, and operation phases of a project due to the harsh construction environment and ecological management issues. Technological environment complexity arises from various reasons, such as the lack of technical standards, specifications, or the existence of diverse technical specifications, particularly in cross-regional MIPs. Market environment complexity refers to the factors that influence the trading and procurement aspects of MIPs, including fluctuations in monetary policies and market trading regulations. Social environment complexity in MIPs refers to the intricacies of social interactions, relationships and dynamics that arise during the planning, implementing and operating MIPs. This complexity arises due to the engagement of multiple stakeholders, public participation, considerations of cultural heritage and the socio-economic benefits (Flyvbjerg et al., 2011; van Marrewijk & Smits, 2016).

3.2. Research hypotheses about the interplay between complexity factors

The diversity and integration of technologies in MIPs have increased the need for an efficient organizational structure and organizational competence. With the rise in technical complexity, organizations must bolster their decision-making capabilities, knowledge, and skills to uphold high performance (Weimann et al., 2013; Xue et al., 2020). Based on the study of the Hong Kong-Zhuhai-Macao Bridge (HZMB) (Zhu et al., 2018) argued that the organizational structure should be flexible and adjusted to the technical factors of the project. Shi et al. (2020) demonstrated that technical complexity led to hierarchical and diversified decision-making structures in megaprojects. Additionally, technical complexity often leads to increased interdependence among tasks, teams, and stakeholders within MIPs. This necessitates effective coordination, communication, and collaboration among different organizational elements, thereby increasing the organizational complexity (Eliwa et al., 2022). Therefore, the following proposal was proposed:

H1: *TEC is positively related to ORG in MIPs*.

In terms of the relationship between organizational complexity and task complexity, Liu et al. (2022) found a significant association between task complexity and contractual and relational governance. Lu et al. (2015) delved into the connection between organizational and task complexity in large projects and uncovered a negative correlation between organizational experience and task complexity, indicating that greater organizational experience led to reduced effort required for task management. Additionally, Hou and Liu (2015) identified human factors as the primary cause of delays in task goals and schedules in large projects. Thus, the following hypothesis was posited:

H2: *ORG is positively related to TAS in MIPs*.

In Tatikonda and Rosenthal's (2000) study on the factors influencing product development projects, technological novelty was identified as a key factor contributing to increased task uncertainty. Lu et al. (2015) indicated that technical errors can lead to increased workload in task resource. Conversely, the adoption of new technologies, such as Building Information Modeling, real-time communication platforms, and virtual collaboration tools, has been shown to reduce task conflict arising from incompatible work processes, resource misallocation (Yang, 2008). Furthermore, increasing technical complexity often leads to task uncertainty. Hence, the following hypothesis was proposed:

H3: *TEC is positively related to TAS in MIPs*.

The internal complexity of MIPs is influenced not only by their internal attributes and characteristics but also by the complexity of the external environment, encompassing ecological, technological, market, and social aspects. Regarding ecological environment complexity, Fahlbusch (2009) indicated that conducting projects in distinctive and complex ecological environments, along with the implementation of tailored measures to enhance the project's environmental adaptability and durability, can potentially result in technical challenges. Xue et al. (2020) found that complex geological conditions, meteorological conditions, and natural disasters directly increased the technical complexity of the project. Additionally, the application of energy-saving technologies also increased the technical complexity in MIPs (He et al., 2015). Therefore, the hypothesis was come up with:

H4: *EE is positively related to TEC in MIPs*.

The intricate and delicate natural environment requires a comprehensive set of ecological and environmental management objectives, thereby increasing the complexity of task goals and resource allocation. For example, during the construction of the HZMB, a significant investment was made to address ecological management issues, leading to a more intricate funding structure for the project. This, in turn, heightened the complexity of the tasks involved (Liu et al., 2018). Additionally, an uncertain ecological environmental often leads to changes in the task plan and schedules in megaprojects (Cazacu & Chitonu, 2018). Thus, the following hypothesis was proposed:

H5: *EE is positively related to TAS in MIPs*.

Chen (2016) demonstrates that differences in regional technological environments and diverse construction standards posed significant challenges to technical management in the context of megaprojects. Diversified technological standards are identified as one of the main factors contributing to increased technological complexity (Xue et al., 2020). Failure to update technical standards in a timely manner can lead to decreased construction efficiency, affecting process completion and increasing technical complexity (Xia et al., 2023). Therefore, the hypothesis was proposed:

H6: *TE is positively related to TEC in MIPs*.

Kim et al. (2005) developed a collaborative engineering model aimed at improving the efficiency of achieving engineering goals by incorporating factors such as building standards and specifications into the model. The multitude of norms associated with the project poses challenges in resource allocation, and the absence of consistent management norms can lead to reduced efficiency in engineering tasks (Ryoo et al., 2010). Thus, the following hypothesis was proposed:

H7: *TE is positively related to TAS in MIPs*.

Kim and Wilemon (2003) identified that market changes during the development of a product project can pose significant challenges to inter-departmental cooperation within project organizations. Awwad et al. (2015) developed models for various market competition scenarios and found that the degree of market competition has a significant impact on contractors' bidding behavior. Moreover, changes in the market environment result in a significant escalation in the complexity of relationships among project participants, leading to alterations in business requirements and increased collaboration complexity among project stakeholders (Gupta et al., 2023):

H8: *ME is positively related to ORG in MIPs*.

Liang and Sheng (2015) found that the presence of unknown factors in the market environment exerted a significant impact on the task complexity related to the investment and finance for the HZMBP. During the pre-construction phase, there might be insufficient accuracy in predicting the project's operating conditions or uncertainties surrounding market investments and fluctuations. These factors can lead to funding challenges and complexity in managing tasks and resources (Zhao et al., 2021). The market environment as well as the impact of the legal system may lead to a complex approval process, increasing the task complexity of MIPs. Thus, the hypothesis was proposed:

H9: *ME is positively related to TAS in MIPs*.

Yuan et al. (2018) concluded that complex relationships resulting from different logics among stakeholders in a project are an important cause of social risk. The studies found that the cultural challenges of multinational projects, as well as situational communicative competence, also affect task complexity (Rodrigues & Sbragia, 2013; Järvenpää et al., 2021). Gao et al. (2018) conducted a study on the HZMBP, which revealed that the social environment, encompassing political factors, cultural dynamics, variations in stakeholders' requirements, and the regional importance of cross-regional mega infrastructure projects, has contributed to the complexity of engineering and construction tasks. Thus, the following hypothesis was proposed:

H10: *SE is positively related to TAS in MIPs*.

3.3. Research hypotheses about the impact of complexity factors on the success of MIPs

The impact of complexity factors on project success has received attention. For example, Odusanya et al. (2021) identified four categories of complexity factors and argued that technical uncertainty, goal and deliverables uncertainty and organizational uncertainty had negative impact on project success. Damayanti et al. (2021b) believed that low social complexity was necessary for the success of large-scale projects. Luo et al. (2017) revealed that both information complexity and goal complexity exerted significant and negative influence on project success. Saad et al. (2022) emphasized that organizational complexity, such as mismanagement of project stakeholders, is a crucial factor contributing to the failure of construction projects in Pakistan.

H11~H17: *Complexity factors* (*TEC*, *ORG*, *TAS*, *TE*, *EE*, *ME*, *SE*) *are negatively related to the success of MIPs*.

Accordingly, the theoretical model of the interplay of complexity factors in MIPs is shown in Figure 2.

4. Empirical research method

4.1. Data collection

This study adopted a purposive sampling approach to empirically investigate the relationship between complexity factors and project success in mega infrastructure projects. Given the limited population of MIPs and the specialized expertise required, respondents were selectively recruited from top management teams with direct experience in MIPs. A pilot study was carried out in January 2022 by distributing the preliminary questionnaire to 33 project managers from key subsidiaries of China Construction Group and China Railway Bridge Bureau. Based on 29 valid responses, the questionnaire was refined – particularly in clarifying complexity factors – before finalization. For the formal questionnaire (from February 2022 to April 2022), the finalized questionnaire was sent to 105 senior managers (e.g., project directors, executives) with in-depth experience via online media (email, WeChat, QQ). Targeted respondents were identified through focusing on professionals associated with landmark projects (e.g., Hong Kong-Zhuhai-Macao Bridge (HZMB), South-to-North Water Transfer Project, Qinghai-Tibet Railway). Snowball sampling method was also used, where initial participants recommended other qualified respondents within their networks.

A total of 83 valid questionnaires were obtained resulting in a response rate of 79%. Despite the small absolute sample size, the purposive sampling ensured high representativeness, as respondents covered nearly all MIPs in China. Each respondent was treated as representing one project, with some having multi-project expertise. This approach aligns with prior studies (e.g., Floricel et al., 2016) that use small but expert samples to analyze complexity impacts. Respondents were required to base answers on their most familiar MIP, ensuring data reliability. The information on the valid respondents is displayed in Table 3.

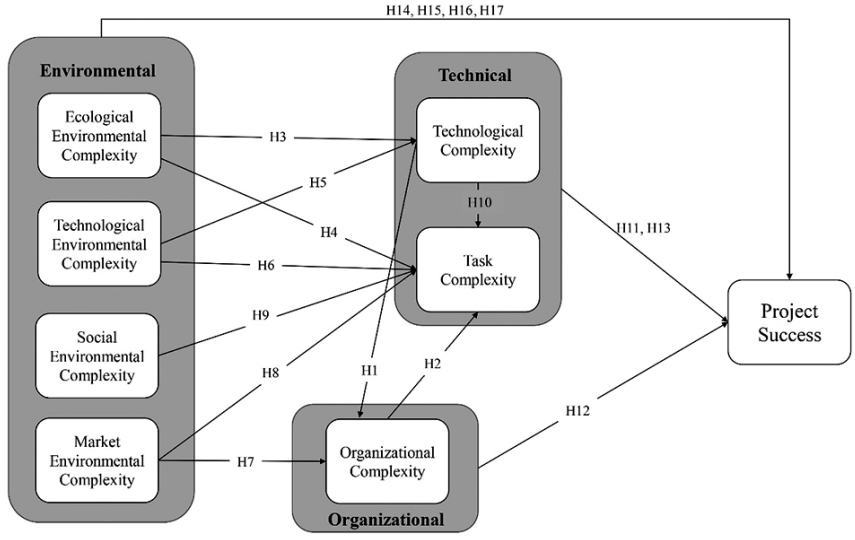


Figure 2. The theoretical model of the interplay of complexity factors in MIPs

Table 3. Statistics on the information of the valid respondents

Items		Number	Percentage
Individual level			
Working experience (year)	0–5	23	28%
	6–10	31	37%
	> 10	29	35%
Affiliated project stakeholder	Owner	37	44%
	General contractor	28	34%
	Consultant team	6	7%
	Design team	4	5%
	Equipment and material suppliers	3	4%
	Scientific research team	1	1%
	Others	4	5%
Project level			
Type of project	Highway and railroad transportation project	53	51%
	Water transportation project	4	4%
	Aviation facility project	5	5%
	Power facility project	8	8%
	Oil and gas project	1	1%
	Coal mines project	2	2%
	Water facility project	5	5%
	Communications facility project	2	2%
	Internet facility project	4	4%
	Others	19	18%

4.2. Research method selection model construction

The complexity of MIPs is characterized by many factors and mixed relationships, which require measures that are highly operational and valid, and that can explore the general laws among the complexity factors to verify the rationality and stability of each association. Common methods to explore the role of independent variables on the dependent variable include multiple linear regression and structural equation modeling. In contrast to multiple linear regression, the structural equation modeling (SEM) method verifies the relationship between one or more independent variables and one or more dependent variables (Urbach & Ahlemann, 2010). There are two main branches of structural equation modeling methods, one is Covariance-based SEM (CB-SEM) and the other is Variance-based SEM.

CB-SEM iterates the model during the computation process, and the factor loadings are estimated simultaneously with the path coefficients. The implied covariance ar-

ray in the model is closest to the sample covariance array. However, the establishment of CB-SEM requires a high number of samples, at least 100, and the latent variables require up to 7 (Marsh et al., 1998; Neil, 2001). Variance-based SEM, also known as PLS-SEM, first performs local iterations of the external model to estimate estimates of the latent variables. Then the parameters in the internal model are estimated. This method requires a small number of samples, which can be calculated with a sample size between 30 and 100 (Hair et al., 2012), and there is no requirement on the number of latent variables, observed variables, and the correspondence. It is suitable for theoretical exploration research.

Based on the above analysis, since the research on the influence of complexity factors in MIPs is still in the exploratory stage, the number of MIPs is limited, and the number of project participants is small. Therefore, the study adopts the PLS-SEM method to measure the influence of complexity factors.

4.3. Variable measurement

The questionnaire measurement items were systematically derived through a two-stage process: (1) axial coding of complexity factors within the MIP framework using grounded theory methodology, and (2) adaptation of validated project success metrics from established scales (Ma & Fu, 2020; Luo et al., 2017). This dual approach ensures both theoretical rigor and measurement validity. The indicators include schedule, quality, cost, satisfaction of project stakeholders and the value of project operation. A Likert 5-point scale was employed to evaluate the qualitative indictors of complexity factors and project success factors, with the scale ranging from "1" to "5" to represent increasing levels of complexity and project success impact. For example, a score of "1" indicates that the goals of the MIP are not achieved and led to significant losses, while a score of "5" indicates that the MIP goals were exceeded with significant additional benefits.

4.4. Model reliability and validity

Cronbach's α and Composite Reliability (CR) were used for reliability testing and the results are shown in Table 4. All thresholds exceeded 0.7, indicating that all complexity factor indicators exhibit good consistency and reliability (Hair et al., 2011). Furthermore, Average Variance Extracted (AVE) and Heterotrait-Monotrait ratio (HTMT) were used to assess convergent and discriminant validity, respectively. As shown in Table 3, all variables exhibit an AVE value exceeding 0.5, while the HTMT values are all below 0.85, signifying that the model demonstrates favorable convergent and discriminant validity (Henseler et al., 2015).

Table 5 shows the factor loading for all variables which was determined by the Bootstrap method of creating 1000 subsamples (Preacher & Hayes, 2008). The results indicate that all external model loadings are above 0.60, indicating that the external model validity is acceptable.

5. Results

Table 6 displays the path coefficients and significance levels, revealing the influence of each complexity factor on the success of MIPs. However, the path coefficients for each complexity factor are found to be statistically insignificant. Therefore, an interaction analysis is performed to investigate the interaction of complexity factors on the success of MIPs.

Table 7 presents the path coefficients and significance levels of the model after incorporating the interaction effect between the complexity factors. The analysis reveals that the paths TEC → ORG, ORG → TAS, TAS → PS, EE → TEC, ME → ORG, SE → TAS, TE → TAS, TE → TEC are statistically significant at the 0.05 level, thereby providing support for hypotheses H1, H2, H3, H5, H6, H7 H9 and H13 (as shown in Figure 3).

Furthermore, the path coefficients of the two significant paths leading to TEC (EE → TEC = 0.261, TE → TEC = 0.274) fall within the range of 0.25 to 0.30, indicating that both EE and TE have a comparable influence on TEC. Regarding the influence of ORG, the path coefficients indicate that TEC (TEC → ORG = 0.521) has more than twice the magnitude compared to ME (ME → ORG = 0.255). Additionally, the path coefficient of ORG in the three variables corresponding to TAS (ORG → TAS = 0.476 SE → TAS = 0.211, TE → TAS = 0.273) is roughly equal to the coefficients of SE and TE. Hence, the findings suggest that the influence of internal complexity on each other is considerably more substantial than the impact of external com-

Table 4. Latent variable reliability and validity statistics

Test items	Cronbach's α	CR	AVE	Discriminant validity							
				EE	TAS	PS	ME	ORG	SE	TE	TEC
EE	0.725	0.879	0.784								
TAS	0.847	0.884	0.523	0.703							
PS	0.810	0.865	0.564	0.350	0.341						
ME	0.783	0.873	0.696	0.674	0.564	0.433					
ORG	0.852	0.888	0.532	0.648	0.828	0.287	0.426				
SE	0.866	0.899	0.599	0.567	0.604	0.358	0.824	0.497			
TE	0.748	0.888	0.798	0.725	0.786	0.407	0.692	0.633	0.652		
TEC	0.748	0.837	0.564	0.545	0.470	0.300	0.317	0.699	0.277	0.523	

Table 5. Factor loading for all variables

Variables	Items	Loading	Sig.
TEC	TEC1	0.694	0.000
	TEC2	0.699	0.000
	TEC3	0.791	0.000
	TEC4	0.811	0.000
ORG	ORG1	0.734	0.000
	ORG2	0.715	0.000
	ORG3	0.761	0.000
	ORG4	0.759	0.000
	ORG5	0.647	0.000
	ORG6	0.759	0.000
	ORG7	0.724	0.000
TAS	TAS1	0.738	0.000
	TAS2	0.789	0.000
	TAS3	0.675	0.000
	TAS4	0.659	0.000
	TAS5	0.726	0.000
	TAS6	0.755	0.000
	TAS7	0.712	0.000
EE	EE1	0.893	0.000
	EE2	0.877	0.000
TE	TE1	0.883	0.000
	TE2	0.904	0.000
ME	ME1	0.852	0.000
	ME2	0.806	0.000
	ME3	0.844	0.000
SE	SE1	0.724	0.000
	SE2	0.717	0.000
	SE3	0.777	0.000
	SE4	0.843	0.000
	SE5	0.758	0.000
	SE6	0.816	0.000
PS	PS1	0.648	0.000
	PS2	0.765	0.000
	PS3	0.708	0.000
	PS4	0.814	0.000
	PS5	0.808	0.000

Notes: PS1 is the schedule; PS2 is the quality; PS3 is the cost; PS4 is the satisfaction of project stakeholders; PS5 is the value of project operation.

Table 6. Statistics on the significance of each complexity factor on the success of MIPs

Path	Original Sample	Sample Mean	Standard Deviation	T Statistics	p values
TEC → PS	–0.199	–0.165	0.204	0.974	0.330
ORG → PS	0.043	–0.014	0.159	0.273	0.785
TAS → PS	–0.067	–0.092	0.181	0.370	0.712
EE → PS	–0.010	–0.003	0.139	0.074	0.941
TE → PS	–0.093	–0.079	0.153	0.606	0.545
ME → PS	–0.160	–0.133	0.178	0.902	0.367
SE → PS	–0.102	–0.142	0.150	0.680	0.497

plexity on internal complexity. This implies that while the external environment does exert a certain level of influence on the complexity of MIPs, the primary drivers of internal complexity are the interactions and interferences among the project's internal subsystems.

Table 7 shows the effect size of the significant paths. According to Cohen (1992), an f^2 below 0.02 indicates a weak evaluation of the model's effectiveness. The results indicate that the f^2 values for the relationships between internal complexity factors exceeds 0.35 (ORG → TAS = 0.426,

TEC → ORG = 0.412), indicating a strong explanatory ability for the internal complexity of MIPs. Whereas external complexity generally demonstrates explanatory power for internal complexity, with all f^2values exceeding 0.02. Combining the path coefficients and f^2, TAS is an internal critical complexity factor, TE is the critical external complexity factor.

Table 8 displays the results of the validity test for the structural equation model. According to Chin (1998), a Q^2 value greater than 0 indicates a good predictive relevance of the model. The R^2 values for TAS and ORG are above 0.33, indicating a high level of explanation for these endogenous latent variables. However, the R^2 values for PS and TEC are moderately weak, suggesting a lower level of explanation for these variables.

The indirect effects of complexity factors on the latent variable (EE, TE, ME, SE, TEC, ORG) of PS are presented in Table 9. Among the paths of indirect influence on PS, the two indirect effect paths of internal complexity factors (TEC, ORG) through TAS are found to be significant.

Table 7. Path coefficient analysis and effective path f^2 statistics

Hypothesis	Path	Original Sample	Sample Mean	Standard Deviation	T Statistics	p values	Result	f^2
H1	TEC → ORG	0.521	0.520	0.102	5.086	0.000	Support	0.412
H2	ORG → TAS	0.476	0.472	0.116	4.120	0.000	Support	0.426
H3	TEC → TAS	–0.096	–0.096	0.096	0.999	0.318	Reject	–
H4	EE → TEC	0.261	0.275	0.125	2.081	0.038	Support	0.062
H5	EE → TAS	0.120	0.122	0.095	1.256	0.209	Reject	–
H6	TE → TEC	0.274	0.273	0.111	2.461	0.014	Support	0.069
H7	TE → TAS	0.273	0.270	0.103	2.658	0.008	Support	0.123
H8	ME → ORG	0.225	0.245	0.096	2.344	0.019	Support	0.077
H9	ME → TAS	0.017	0.005	0.123	0.135	0.892	Reject	–
H10	SE → TAS	0.211	0.227	0.101	2.103	0.036	Support	0.082
H11	TEC → PS	–0.042	–0.054	0.154	0.276	0.783	Reject	–
H12	ORG → PS	–0.032	0.004	0.208	0.155	0.877	Reject	–
H13	TAS → PS	–0.363	–0.399	0.093	3.916	0.000	Support	0.152
H14	TE → PS	–0.135	–0.125	0.161	0.838	0.402	Reject	–
H15	EE → PS	–0.026	–0.020	0.156	0.168	0.886	Reject	–
H16	ME → PS	–0.189	–0.196	0.206	0.921	0.357	Reject	–
H17	SE → PS	–0.091	–0.110	0.199	0.458	0.647	Reject	–

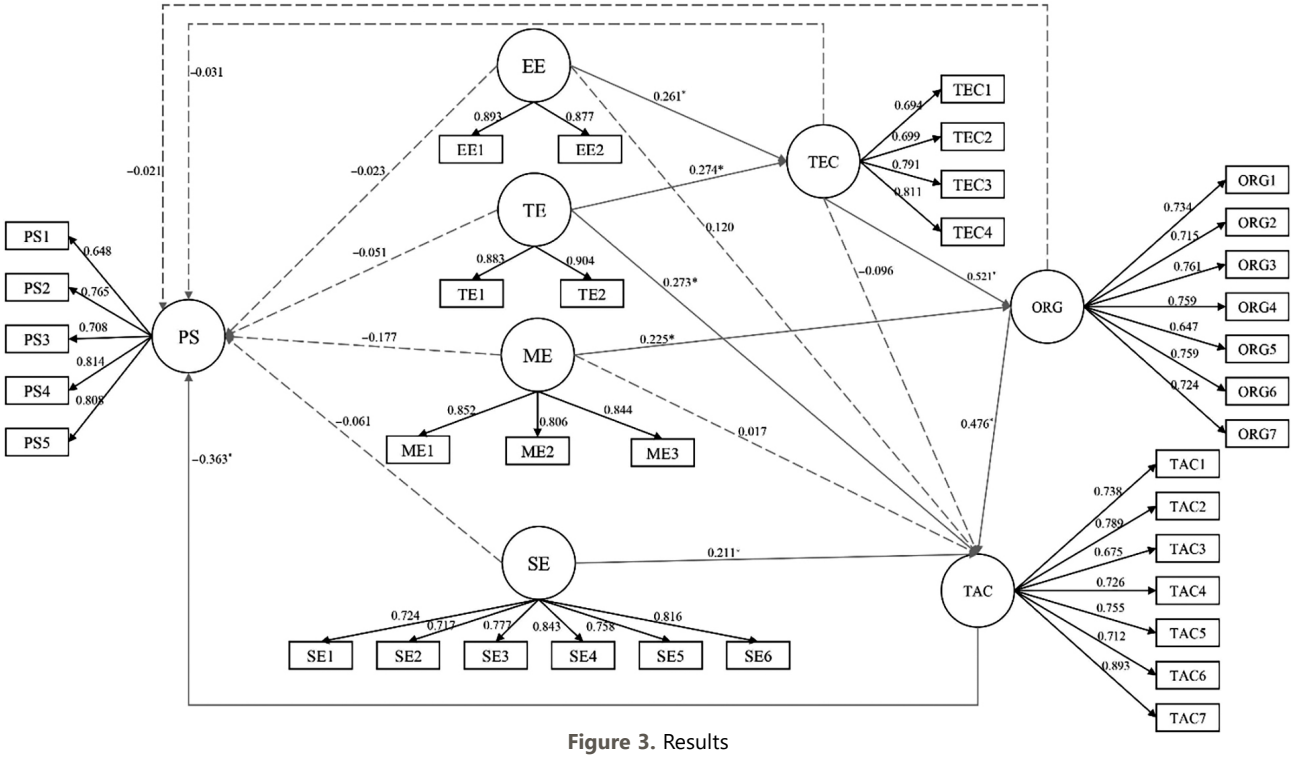


Figure 3. Results

Table 8. Statistics of Q^2, R^2 information containing effective path models

Variables	SSO	SSE	Q^2	R^2	Adjusted R^2
TAS	581.000	374.868	0.307	0.627	0.612
PS	332.000	233.692	0.034	0.132	0.121
ORG	581.000	366.180	0.186	0.379	0.363
TEC	332.000	239.309	0.108	0.219	0.200

Table 9. Indiect effects and their significance statistics

	Original Sample	Sample Mean	Standard Deviation	T Statistics	p values
The indirect effects of external complexity					
EE → TEC → ORG → TAS → PS	–0.023	–0.028	0.020	1.188	0.235
TE → TEC → ORG → TAS →PS	–0.025	–0.027	0.017	1.464	0.143
TE → TAS → PS	**–0.099**	**–0.108**	**0.049**	**2.009**	**0.045**
ME → ORG → TAS → PS	–0.039	–0.046	0.023	1.693	0.091
SE → G&R → PS	–0.077	–0.090	0.044	1.758	0.079
The indirect effect of the internal complexity					
TEC → ORG →TAS → PS	**–0.090**	**–0.099**	**0.042**	**2.138**	**0.033**
ORG → TAS → PS	–0.173	–0.190	0.068	2.548	0.011

6. Discussion

6.1. The interplay of multidimensional complexity in MIPs

Empirical results indicate that the explanatory power of single complexity factors on project success is limited, whereas considering the interplay of complexity factors significantly improves the explanation power of project success. Specifically, the results support most of the hypotheses regarding the interaction between complexity factors, but H3, H5 and H9 are rejected.

H3 which hypothesized a positive relationship between TEC and TAS in MIPs, was not supported. While prior research (Baccarini, 1996; Andringa et al., 2022) often conflates these concepts by defining technology through task performance metrics, this study distinguishes them operationally. Our broader conceptualization of TAS incorporates additional dimensions like resource allocation and engineering risks, potentially explaining the rejected hypothesis.

H9 proposing a positive relationship between ME and TAS in MIPs, has been rejected. One possible explanation is that government intervention weakens the influence of market environment complexity on the implementation of MIPs, such as the acquisition of resources and the achievement of project goals. Our results corroborate Eren's (2019) assertion that government strategic initiatives and policy frameworks serve as primary drivers for MIPs, effectively buffering against market environment complexity during project execution. This conclusion is further substantiated by Oti-Sarpong et al.'s (2022) parallel findings.

Overall, the impact of external complexity on internal complexity is weaker than the interaction among internal complexity factors. The main reason is that TEC and ORG are primarily rooted in the inherent characteristics of MIPs, rather than being influenced by environmental changes. The dynamics of TEC and ORG are primarily driven by internal factors within the project rather than external factors. For example, once the engineering design is finalized, TEC becomes an inherent aspect of the project. During construction and operation phases, continuous identification and resolution of technical issues occur to achieve desired system functionality. This ongoing process causes fluctuations in TEC, which can increase, or decrease depending on challenges and implemented solutions. Furthermore, TAS is also a critical internal complexity factor. This indicates that engineering tasks serve as instrumental tools employed by managers in constructing engineering entities. TAS evolves in tandem with changes happening in other subsystems within the project. As the project advances and other project elements undergo modifications or developments, TAS adjusts and mirrors these changes.

The significant influence of external complexity on internal complexity validates the understanding that MIPs have far-reaching implications and involve a wide range of stakeholders, with their complexity being influenced by the surrounding environment. This highlights the importance of considering environmental factors that contribute to the complexity of such projects, as they cannot be overlooked. The West-East Natural Gas Transmission Project's traversal through ecologically sensitive zones engendered specialized construction requirements (Cheng, 2003), while the Three Gorges Dam project confronted compound challenges encompassing ecosystem conservation and large-scale population resettlement, mandating persistent attention to environmental complexity throughout its lifecycle (Li, 2017). Given the intricate and evolving natural and human environments, effective complexity management of MIPs necessitates the ability to adapt to these complexities.

6.2. The effect of complexity factors on the success of MIPs

Merely the hypothesis proposing that task complexity significantly influences the success of MIPs is supported among the hypotheses regarding the impact of single complexity factors. The empirical results corroborate Luo et al.'s (2017) findings regarding the non-significant effects of TEC, ORG and various environmental complexity dimensions - including EE, TE, ME, and SE – on project success outcomes. However, Ma and Fu (2020) indicated that the configuration of complexity factors significantly impacts project success. Therefore, this study reinforces the conclusion that single complexity factors alone are insufficient to explain the success of MIPs. Instead, considering the interplay among complexity factors, particularly the linkage between external and internal complexity factors, provides a better explanation for project success.

Regarding the impact of complexity factors on project success, this study reveals that among the internal complexity, TAS exhibits a significant negative impact on the success of MIPs. However, the impact on each success dimension may vary. Although ORG and TEC do not directly impact on the success of MIPs in a significant manner, they can still exert an indirect influence on the success of these projects through their effects on TAS. Overall, it is evident that internal complexity factors, such as TAS, play a more dominant role in shaping the success of MIPs.

This study builds the path of the correlation effect between the complexity factors of MIPs on project success. The findings of some scholars show that the effect of environmental complexity factors on project success is not significant, and others have investigated the effect of the combination of environmental complexity factors and other complexity factors on project success (Luo et al., 2017; Ma & Fu, 2020). This study found that environmental complexity factors can indirectly affect project success through internal complexity factors. Technical environmental complexity factors indirectly affect project success through task complexity. The study by Luo et al. (2017) concluded that neither technical complexity nor organizational complexity has a significant direct impact on project success. However, this study elucidates a more nuanced pathway through which these complexities influence project success. Specifically, it demonstrates that organizational complexity indirectly affects project success by influencing task complexity, while technical complexity exerts its indirect impact through its effect on organizational complexity. This finding underscores the importance of considering the interplay between these complexity factors, rather than their isolated effects, in understanding the success of mega infrastructure projects.

6.3. Implications

The theoretical implications of this research are twofold. Firstly, this study significantly advances complexity theory in project management by establishing a clear link between external and internal complexity factors. Our validated framework demonstrates that while external complexities – such as ecological, technological, market, and social factors – do not directly impact project success, they significantly influence internal complexity dimensions, including technical, organizational, and task complexity. These internal dimensions, in turn, have a substantial effect on project outcomes. This mediation model provides a more nuanced and comprehensive understanding compared to previous unidimensional approaches (Luo et al., 2017; Ma & Fu, 2020). Secondly, the study contributes to institutional theory by elucidating how government intervention moderates the impact of market complexity. The buffering effect of policy frameworks, as highlighted by Eren (2019) and Oti-Sarpong et al. (2022), explains why certain complex relationships were rejected (e.g., H9). This suggests that institutional factors should be incorporated as boundary conditions in future complexity models, thereby enriching the theoretical understanding of how external environments shape project complexity and success.

The findings of this study offer actionable insights for improving the governance, decision-making, and execution of Mega Infrastructure Projects (MIPs). First, in terms of project governance, proactive environmental management should be a cornerstone of project planning. By institutionalizing early intervention strategies, as suggested by Morrissey et al. (2012), project teams can mitigate ecological impacts before they exacerbate technical complexities. Additionally, developing complexity-aware organizational structures is crucial. Flexible hierarchies that can adapt to evolving task complexities, especially in resource allocation and risk management, will enhance project resilience and responsiveness. For decision-making processes, adopting process learning approaches can significantly improve project outcomes. Establishing feedback loops through simulation modelling for technical complexity, scenario planning for market fluctuations, and stakeholder workshops for social complexity will enable more informed and adaptive decision-making. Furthermore, creating integrated knowledge platforms that combine Building Information Modelling (BIM) systems with environmental monitoring data, supply chain management tools, and stakeholder engagement portals will facilitate real-time data integration and enhance project transparency and coordination. Besides, capability building is another crucial area, requiring investments in adaptive competencies. Cross-disciplinary training programs and specialized certifications in complexity management can equip teams with the skills to navigate multifaceted challenges. Additionally, maintaining lessons-learned databases, such as those documenting the Three Gorges Dam's ecological and resettlement strategies, provides valuable benchmarks for future projects. Finally, governments play a pivotal role in shaping the environment for MIPs. Policymakers should develop standardized complexity assessment frameworks to systematically evaluate and manage project complexities. Early-warning systems for market volatility and incentive mech-

anisms for proactive complexity mitigation will encourage project teams to adopt best practices and reduce the likelihood of adverse outcomes. By implementing these practical recommendations, stakeholders can better manage the inherent complexities of MIPs, leading to improved project outcomes and greater overall success.

7. Conclusions

This study utilized grounded theory to identify complexity factors within MIPs based on the TOE framework. A comprehensive evaluation index system for the complexity of MIPs, integrating both internal and external complexity, has been developed. This system consists of 7 primary indicators and 31 secondary indicators. Besides, a research hypothesis model has been proposed through theoretical deduction, which explores the relationships between complexity factors and their impact on the success of MIPs. An empirical study was conducted through a questionnaire survey. The results show that external system complexity has a significant positive impact on internal complexity within MIPs. However, the influence of external system complexity on internal complexity is relatively weaker compared to the reciprocal influence of internal system complexity. Additionally, it is found that complexity has a negative impact on the success of MIPs. However, the explanatory power of single complexity factors in predicting the success of MIPs is low. The suggestions for complexity control of MIPs have been provided through utilizing comprehensive and integrated tools for integrated management and increasing the adaptive capacity of complexity management.

There are some limitations and need to be further studied in the future. Due to the limited sample size, it was unable to confirm whether the project type, working experience of respondents, and their organizational affiliation have moderate effects on the relationship between complexity factors and the success of MIPs. Besides, the mediating role of complexity degradation needs further exploration. Moreover, the sample of this study is currently limited to China, and the MIPs studied are all Chinese projects, a limitation that may affect the direct generalization of the results. However, we believe that the results of the study can be generalized to a certain extent to MIPs in other countries or regions with similar environments to China. China, as a developing country, faces challenges in the construction of MIPs such as rapid urbanization and unequal distribution of resources, which are common to many developing countries. Therefore, the complexity factors and their interactions identified in this study may have some reference value for MIPs projects in similar environments. At the same time, the research methodology proposed in this study provides a novel and systematic way of thinking about complexity research in MIPs, despite the differences in institutions and management practices in different regions, which may lead to different influencing roles among complexity factors. By combining the TOE framework and grounded theory to identify complexity factors and using PLS-SEM to verify their interactions, this approach is highly replicable. Based on this approach, other researchers can adapt the research design, expand the sample size and project scope, and apply it to MIPs projects in different countries and regions, thus producing more generalizable findings.

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Author contributions

KNL and QPM conceived the study and were responsible for the design and development of the data analysis; YJP and YDZ were responsible for data interpretation; YJP wrote the first draft of the article; KNL undertook its revision and submission.

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APPENDIX

Table A1. The basic information about typical MIPs

Project Code	Typical Project Title	Project type	Project Scale	Project Features	Construction Period
HZ	Hong Kong-Zhuhai-Macao Bridge (HZMB) Project	Highway and Railway Transportation Facilities	The immersed tube tunnel is nearly 6 km long with a depth of about 40 m, 2 large artificial islands Cross-region: Hong Kong, Macau, Guangzhou	Crossing Different Social Institutions Project	2009–2018
NS	South-to-North Water Transfer Project	Water Facilities	Planning the final scale of water transfer 44.8 billion m^3 Cross-region: from the Yangtze River Basin in the east, center and west to North China and the Huaihai Plain and the northwest region	Transregional water projects	2002–present
QZ	Qinghai-Tibet Railway Project	Highway and Railway Transportation Facilities	Total length of 1956 km, crossing the plateau permafrost zone length of 632 km Cross-region: Qinghai, Tibet	Harsh construction environment and technical difficulties	1958–2006
SX	Three Gorges Dam Project	Water Facilities	The dam has an axial length of 2309.5 m, a reservoir capacity of 39.3 billion m^3, and a flood control capacity of 22.15 billion m^3. Cross-region: Yichang City, Hubei Province to Chongqing Municipality	Far-reaching social impact	1994–2009
XD	West-East Natural Gas Pipeline Project	Oil and gas facility	Total pipe length over 20,000 kilometers Cross-region: Xinjiang to Shanghai	Cross-regional energy projects	2002–present
ZE	China-Russia crude oil pipeline project	Oil and gas facility	With a total length of 1,030km, the pipeline is responsible for 58% of China's onshore crude oil import. Cross-region: Skovonodino, Russia to Daqing, Heilongjiang Province	Cross-border energy projects	2009–2018

Table A2a. Extraction of technical complexity factors for MIPs based on grounded theory

Example of reference nodes	Open coding nodes	Spindle coding nodes	Selective coding nodes
XD: Large use of foreign core equipment, technology constraints	High-tech components (a1)	Diversification of technology (A1)	Technological complexity (TEC)
QZ: Lower traffic levels along the highway	Legitimacy of the use of new technologies, processes, materials and patents (a2)	Difficulty of technology and application risk (A2)	
NS: Increase in the number and standard of cross-drainage structures	Highly demanding and difficult design of structures and materials (a3)		
ZE: Innovative use of technology, workmanship	Technically challenging (a4)		
HZ: The installation of pipe joints has a more complex construction process	Complexity of processes (a5)	Convergence of construction processes (A3)	
HZ: Technically difficult, with many engineering interfaces	Multiple construction intersections (a6)		
HZ: Follow-up monitoring of pipe joints at a later stage of installation	High demand for process completion (a7)	Completion of processes (A4)	

End of Table A2a

Example of reference nodes	Open coding nodes	Spindle coding nodes	Selective coding nodes
NS: Risk of non-availability of committed funds	Limited funding (a8)	Limitations of quantity and quality of resources (A5)	Task complexity (TAC)
HZ: There are few market resources that can match, and a lack of quality resources	Lack of market resources to meet demand (a9)		
HZ: High construction equipment requirements	High demand for construction equipment (a10)		
QZ: Very tight schedule for key projects	Construction schedule, time constraints (a11)		
NS: Complexity of local sharing of investment projects	Rationalization of resource allocation and difficulty in scheduling resources (a12)	Resource allocation and scheduling (A6)	
HZ: Guangdong, Hong Kong and Macao to jointly form a PMU to mobilize non-capital funding through loans	Complex funding structure (a13)	Complexity of capital structure (A7)	
NS: Hydraulic tunnels demand high lining quality	High engineering and construction goals and management requirements (a14)	Diversification of construction goals(A8)	
HZ: Diversified decision-making objectives	Diversification of engineering and construction goals (a15)		
HZ: Complex linkages among factors with strong systemic integrity	Integration of interrelated engineering tasks (a16)	Relevance and integrity of engineering tasks (A9)	
HZ: The project management interface is extremely complex	Engineering Project Management Interface Multi (a17)		
SX: Geography and many other complex issues	Dynamics of objectives, mandates (a18)	Dynamism of engineering tasks (A10)	
NS: The risk management system for safety movement is not yet complete	Lack of effective risk management system and methodology (a19)	Engineering changes and risks (A11)	
NS: Insufficient attention to safety scheduling risk management in some sections of the Eastern Route project	Inadequate focus on risk management (a20)		
ZE: Russia's oil export revenues plummet, domestic economic crisis severe	Further evolution of risk (a21)		
HZ: Higher number of changes in works; significant investment in temporary works costs	High probability of engineering changes and severe losses (a22)		
HZ: No proven experience to draw on, lots of uncharted territory	Project benefits unknown (a23)		
NS: Timely delivery of locally committed shared investments	Uncertainty in the financing process (a24)		

Table A2b. Extraction of organizational complexity factors for MIPs based on grounded theory

Example of reference nodes	Open coding nodes	Spindle coding nodes	Selective coding nodes
HZ: At the management level, it is a serious challenge for the whole bridge steel structure manufacturing industry	Irrational organizational divisions (a25)	Organizational structure and governance (A12)	Organizational complexity (ORG)
HZ: Unclear segregation of duties and costs	Inadequate division of authority and responsibility between organizations (a26)		
NS: Multiple administrations	Numerous teams and a wide span of hierarchies (a27)	Temporal and spatial differentiation of teams (A13)	
HZ: Differences in industry categories, differences in contract content, gaps in corporate culture, differences in team quality	Inter-organizational differences and imbalances (a28)		
QZ: Decision object laws are not easy to cognize	Complexity and dynamics of inter-organizational relationships (a29)	Dynamism of organizational relationships (A14)	

End of Table A2b

Example of reference nodes	Open coding nodes	Spindle coding nodes	Selective coding nodes
HZ: Adoption of the principles of "rapprochement" and "consensus"	Low level of inter-organizational trust (a30)	Collaboration and information sharing among teams (A15)	Organizational complexity (ORG)
HZ: Communication is inefficient and in a state of information asymmetry	Asymmetric information and inefficient communication between organizations (a31)		
HZ: Lack of well-established rules of procedure and coordination mechanisms	Lack of well-coordinated inter-organizational management mechanisms (a32)		
HZ: Strengthening internal coordination within the contractor, rationalizing the deployment of key resources and joint action by multiple actors	High volume of inter-organizational linkages (a33)		
XD: The smooth flow of engineering information becomes a key issue	Information-rich and complex relationships during project planning, construction, and maintenance (a34)		
ZE: Innovate the management model	Inexperienced and unprepared managers (a35)	Capability and mobility of managerial staff (A16)	
ZE: Strengthening control discipline	Moral turpitude and lawlessness of managers (a36)		
HZ: Difficulty in building teams and stabilizing personnel	Stability of staff within the organization (a37)		
HZ: Most of the tenders are the first of their kind in the country and there is no mature experience to draw on	High level of uncertainty during the bidding and execution of works (a38)	Risk of engineering procurement (A17)	
HZ: Interface issues between 11 construction bids, 8 supervision bids and 4 consultant-type bids within the main project	Multiple projects with multiple contract management components (a39)	Complexity of contract management (A18)	
HZ: Complexity of contract management for the main works	Multiple types of contracts and complex contractual relationships (a40)		

Table A2c. Extraction of environmental complexity factors for MIPs based on grounded theory

Example of reference nodes	Open coding nodes	Spindle coding nodes	Selective coding nodes
XD: Poor environment for construction work	Dynamic changes and uncertainties in the construction operating environment (a41)	Harsh construction environment (A19)	Ecological and environmental complexity (EE)
NS: Changes in geological conditions	Construction Safety Hazards (a42)		
ZE: Crewing for winter construction in alpine regions	Harsh environment for construction work (a43)		
HZ: Prolonged monotonous construction at sea can lead to psychological imbalance	Workplace environments that cause physical and mental health problems for employees (a44)		
SX: Still no full agreement on migration, sediment, environment, ecology, etc.	Complexity of ecological governance (a45)	Complexity of ecological environment governance (A20)	
NS: There are still a lot of shortcomings and relative weaknesses in water transfers	Backward technological environment and lack of relevant standards and norms (a46)	Incomplete policies, standards, and specifications (A21)	Technical environment Complexity (TE)
HZ: Differences in engineering design and construction standards among Guangdong, Hong Kong and Macao	Diversification of construction standards and technical specifications for cross-regional projects (a47)	Diversification of cross-regional technical standards (A22)	
HZ: The importance of the project varies from place to place, and the strength of its promotion is not consistent from place to place	Cross-regional financing concepts, trading habits differ greatly (a48)	Differences in cross-regional financing policies (A23)	Market environment complexity (ME)
HZ: Although the program has substantially reduced the cost of investment for private firms through spin-off financing, with inflation and exchange rate changes	Changes in international or domestic markets (a49)	Dynamism of international or domestic markets (A24)	

End of Table A2c

Example of reference nodes	Open coding nodes	Spindle coding nodes	Selective coding nodes
QZ: The traditional enforcement model is not effective in preventing and reducing violations of the law	Inadequate laws, systems and policies related to the contracting model and bidding process (a50)	Imperfection of legal systems (A25)	Market environment complexity (ME)
HZ: Private investment behavior often creates undesirable contradictions with the objective of promoting socio-economic development	Irregularities in the market (a51)		
SX: Unreasonable compensation, corruption of local officials and unfulfilled promises	Legal and institutional barriers to financing models (a52)		
NS: Changes in the different levels of subjects of interest and their regional interests	Diversity, divergence and even confrontation of stakeholder needs (a53)	Diversity of stakeholder demands (A26)	Social environmental complexity (SE)
HZ: Individuals have up-to-date, idiosyncratic information that is often not shared with others in decision-making discussions and does not guide decision-making	Information asymmetry and inefficient communication between stakeholders (a54)		
NS: The work of land acquisition and migration involves complex interests	Stakeholder relationships, changes in needs (a55)	Dynamism of stakeholder demands (A27)	
XD: Some other policy or economic change occurs	Stability of international and national political forms (a56)	Stability of international and domestic politics (A28)	
HZ: The Bridge is the first time that the governments of Guangdong, Hong Kong and Macao have cooperated in the construction of the Bridge	Pluralism in cross-regional political systems (a57)	Differences in cross-regional political environments (A29)	
NS: Recognizing the existence of disharmony in society	Large differences in culture and living habits across regions (a58)	Differences in cross-regional cultures (A30)	
SX: Wide appeal to local governments and civil society	High social interest in the project(a59)	Social attention and impact of the project (A31)	
NS: Xiangfan, a water transfer area, has development opportunities	The political, social, economic and technical significance of the completion of the project is far-reaching(a60)		