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Research Article

Assessment of the Digital Transformation in the Construction Industry: A Case Study of the Yangtze River Economic Belt

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Abstract

China's construction industry is undergoing rapid digitalization through the adoption of Building Information Modeling (BIM), the Internet of Things (IoT), and Artificial Intelligence (AI). However, the spatial distribution of digital adoption remains poorly understood. This study assesses digital transformation levels across the Yangtze River Economic Belt (YREB) from 2011 to 2021, examining regional disparities and the barriers impeding further digitalization. Utilizing a comprehensive evaluation index system encompassing digital infrastructure, investment, applications, and sustainability indicators, the analysis reveals pronounced spatial heterogeneity. The downstream region exhibits advanced digital adoption, while the upstream and midstream regions encounter significant challenges related to inadequate technological infrastructure, insufficient investment, and digital skill shortages. The regional gap between the highest and lowest provincial scores reaches 0.226 in 2021, demonstrating persistent disparities. The study contributes a validated assessment framework, theoretical grounding through the

Technology-Organization-Environment (TOE) framework, and policy recommendations differentiated by regional readiness levels. These findings have significant implications for policymakers seeking to promote balanced digital transformation across the YREB.

Keywords: Digital Transformation, Construction Industry, Yangtze River Economic Belt, BIM, IoT, AI, Regional Disparities, Technological Infrastructure, Policy Recommendation.

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1. Introduction

The construction industry, a cornerstone of economic development and urbanization, is experiencing a paradigm shift driven by the widespread adoption of digital technologies. Building Information Modeling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing are fundamentally transforming project planning, execution, and management practices ([1-3]. These technologies promise significant improvements in efficiency, cost-effectiveness, sustainability, and safety—addressing long-standing challenges that have historically characterized the sector [4].

The Yangtze River Economic Belt (YREB), encompassing 11 provinces and municipalities along China's longest river, represents one of the nation's most economically significant regions. Home to approximately 40% of China's population and generating over 45% of the national GDP (National Bureau of Statistics, 2022), the YREB is critically important to the construction industry and its digital transformation. The region's construction sector is essential to its ongoing urbanization and infrastructure development, accounting for a substantial portion of regional employment and economic output.

Despite the transformative potential of digital technologies, their adoption in the construction industry remains unevenly distributed across space and scale [4, 5]. While large, technologically sophisticated firms in the YREB's coastal provinces have successfully integrated digital tools into their operations, numerous firms, particularly in inland provinces, continue to rely on traditional, paper-based processes. This digital divide is shaped by multiple interacting factors, including high implementation costs [6], a shortage of digitally skilled personnel, organizational resistance to change and inadequate technological infrastructure [6].

Previous research on digital transformation in construction has primarily focused on national-level patterns[1], individual technology assessments [3], or firm-level case studies. Studies examining sub-national spatial variations in digital adoption across the YREB are conspicuously absent. This gap is significant because understanding spatial disparities is essential for designing effective, regionally differentiated policies to promote balanced digital transformation.

This study addresses this gap by systematically assessing the level of digital transformation in the YREB's construction industry from 2011 to 2021. Drawing upon official statistical data from 11 provinces, this research develops a comprehensive evaluation index system encompassing four core dimensions: digital infrastructure, digital investment, digital applications, and sustainable development. Through the application of the Entropy-Weight Method, the study constructs composite digital transformation scores, enabling comparative analysis across provinces and sub-regions. The analysis is theoretically grounded in the Technology-Organization-Environment (TOE) framework, which provides a systematic lens for understanding regional disparities.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on digital transformation in construction, identifying research gaps that this study addresses. Section 3 presents the methodology, including data collection procedures, the evaluation index system, the analytical approach, and robustness checks. Section 4 reports the empirical findings, analyzing regional patterns and temporal trends. Section 5 discusses the implications of the findings for theory, policy, and practice. Section 6 concludes and identifies directions for future research.

2. Literature Review

The construction industry is experiencing a dramatic digital transformation, which is driven by the introduction of new technologies, including Building Information Modeling (BIM), the Internet of Things (IoT), and Artificial Intelligence (AI). The innovations are expected to improve efficiency, reduce costs, enhance sustainability, and boost the overall performance of projects. Nevertheless, regardless of these developments, the implementation of digital tools is still unevenly spread throughout the industry, which depends on such factors as cost, the ability of the workforce, and organizational obstacles. This part investigates the motivators, obstacles, and current issues of the digital transformation in the construction sector, with direct references to the Yangtze River Economic Belt (YREB).

2.1 Digital Transformation in the Construction Industry

Digital transformation in the construction industry is the use of digital technology to streamline and automate the processes that used to be handled manually and through the old-fashioned systems. It covers a wide area of technologies, such as BIM, IoT, AI, cloud computing, and big data analytics. The tools provide an opportunity to improve decision-making, resource management, and operational processes. [1].

- **Building Information Modeling (BIM):** BIM is a revolutionary technology used in the construction industry that enables one to create detailed 3D models of buildings and infrastructures. It supports improved design coordination and project management as well as lifecycle management through the ability of real-time collaboration and data sharing of project teams. The BIM also helps in minimizing design errors and optimizing scheduling, as well as minimizing costs. A study by [7] shows how BIM results in substantial time and cost savings benefits due to its capability to forecast the project results and eliminate the risks prior to the start of the construction.
- **Internet of Things (IoT):** IoT is transforming the construction site operations in the sense that activities of materials, machinery, and workers can now be tracked in real time. Construction equipment and materials can have sensors that gather information that can be discussed to gain an insight into their operations. The technology assists in resource allocation optimization, minimization of downtimes, and improved safety at construction sites. As it is stated in [8], IoT has played a significant role in the efficiency of the construction process, as predictive maintenance features to avoid equipment breakdowns and increase the life cycle of expensive equipment have become possible.
- **Artificial Intelligence (AI):** AI in construction makes use of machine learning algorithms to enhance the project planning, scheduling, and resource management. The AI systems can process a high volume of data and forecast possible delays, optimize human and material use, and come up with cost-efficient ways to conduct the project. A study conducted by [9] reveals that AI-driven tools are capable of automatizing decision-making and may also spot patterns that are not perceived by human operators, thus enhancing the performance of a project and minimizing the possibility of cost increasest

Although these technologies have potential, their acceptance by most construction industries has been hampered by a number of obstacles, particularly in developing countries, like the upstream and midstream regions of the Yangtze River Economic Belt. Studies by [10]. suggest that despite the potential of these technologies, many construction firms especially small and medium-sized enterprises (SMEs) remain hesitant to embrace digital transformation due to the financial investment and the complexity of new systems.

2.2 Mechanisms Driving Digital Transformation

We can consider efficiency improvement, cost reduction, and sustainability as the primary drivers of the digital transformation in the construction industry. These drivers are closely interconnected; as efficiency improves, costs decrease, and sustainable practices often lead to long-term savings.

- **Improvement in efficiency:** The construction industry is known to be characterized by inefficiency in terms of cost overruns, time wastage, and wastage of resources. Digital technologies solve those problems, as they enhance communication and collaboration and manage workflow. Examples include BIM, which enables project teams to easily visualize the whole project in 3D, identify design clashes during early stages, and make changes before the construction process starts, thereby saving them the cost of errors. IoT allows real-time monitoring of materials, equipment, and labor force, making sure that resources are used in the most efficient way and that delays are avoided [11].
- **Cost Reduction:** Cost reduction is one of the major advantages of digital transformation. Such technologies as BIM and AI allow planning and budgeting the project more correctly and prevent the risk of unexpected costs. Predictive analytics are optimized with AI to maximize the buying of materials, whereas predictive maintenance is reduced with the help of the IoT to minimize expensive equipment failures. It is particularly when used in identifying inefficiencies where AI-based tools can prove especially useful, as they can help companies distribute resources more efficiently and minimize waste, as stated in [12, 13].
- **Sustainability:** With the increased environmental concerns about the construction industry, digital transformation has a major role to play in ensuring sustainability. During the design stage, BIM will be able to simulate the amount of energy used, and therefore the architect can select more sustainable building materials and construction techniques. Moreover, IoT sensors are used to track energy consumption at construction sites, which guarantees that energy is utilized properly and minimizes environmental impact on the projects. The combination of these digital tools is sustainable, and it is one of the factors that would reduce carbon footprints and waste during construction [14].

2.3 Barriers to Digital Transformation

Despite the documented benefits of digital technologies in construction, several significant barriers impede their widespread adoption. These barriers, which interact and compound each other, are particularly pronounced in less economically developed regions.

- **Financial Constraints:** The implementation of BIM, IoT, and AI systems entails substantial capital investment in hardware, software, and infrastructure, coupled with ongoing maintenance and upgrade costs. For small and medium-sized enterprises (SMEs), which constitute the majority of construction firms in the YREB, this financial burden is often prohibitive [15]. The upfront costs are particularly challenging when the return on investment is uncertain or long-term [16]. This financial barrier is most acute in upstream provinces, where construction firms typically have more limited financial resources and access to credit.
- **Shortage of Skilled Workforce:** A critical impediment to digital transformation is the scarcity of digitally skilled personnel capable of effectively deploying and managing advanced technologies. Many construction firms lack employees with the necessary proficiency in BIM modeling, IoT device management, AI systems, and data analytics [1]. This skills shortage is particularly pronounced in the upstream and midstream regions of the YREB, where educational institutions offer fewer technology-focused programs, and continuing education opportunities for current workers are limited [1]. The skills gap creates a vicious cycle: without skilled personnel, firms cannot effectively deploy digital technologies, reducing demand for training, which perpetuates the skills shortage.
- **Resistance to Change:** Most construction companies are apprehensive about using digital technologies because of resistance to change. The construction industry is a highly conservative one, as it refers to proven methods that have been working for decades. Resistance to new technologies within an organization can be one of the major barriers to digital adoption since companies might be afraid of breaking their established workflow and meeting the extra expenses. This resistance can only be overcome with good leadership, effective communication, and an innovation-encouraging culture [17].
- **Integration Problems:** The process of adopting new digital technologies and combining them with old systems may be tedious and lengthy. A lot of construction

companies are still using old software and processes, and thus, they cannot easily integrate new technology such as BIM and AI. Interoperability is also a challenge due to the lack of standardization between various digital platforms, which may affect the sharing of data and collaboration between various technologies [10].

2.4 Research Gaps

A systematic review of the literature reveals three significant research gaps that this study addresses:

Gap 1: Limited Spatial Analysis of Digital Transformation*

While the scholarly literature has extensively examined digital transformation in the construction industry [1, 3, 4, 18] the majority of studies have focused on national-level adoption patterns or individual firm-level case studies. Research examining sub-national spatial variations remains conspicuously absent, particularly in the context of economically significant regions such as the YREB. This study fills this gap by providing a comprehensive spatial analysis of digital transformation disparities across 11 provinces spanning three distinct economic sub-regions.

Gap 2: Fragmented Assessment Frameworks

Existing assessments of digital transformation in construction tend to focus on individual technologies in isolation, BIM adoption studies [7, 19], IoT implementation research [20, 21], or AI applications [21] without integrating these components into a holistic framework. This fragmented approach obscures the interrelated nature of digital ecosystems and fails to capture the synergies between technologies. This study addresses this gap by developing a multi-dimensional assessment framework that encompasses infrastructure, investment, applications, and sustainability dimensions simultaneously.

Gap 3: A theoretical Explanations of Regional Disparities

Prior studies have described regional differences in technology adoption without providing explanatory theoretical frameworks [22]. This atheoretical approach limits the generalizability of findings and weakens the theoretical contribution to the field. This study fills this gap by grounding the analysis in the Technology-Organization-

Environment (TOE) framework, providing a theoretically informed explanation for the observed regional disparities.

3. Data Collection and Research Methodology

This research will evaluate the extent of the construction industry in the Yangtze River Economic Belt (YREB) with regard to digital transformation. In order to do so, we have adopted a mixed approach method, which involves both the quantitative and the qualitative methodology. In the methodology section, the researcher provides the data collection process, the index system used to evaluate digital transformation, and methods to be used to analyze the data. Also, the data presentation section presents the main findings regarding the obtained data and explains the interpretation of the findings about regional differences in the use of digital technologies in detail.

3.1 Data Collection

The main data that was used to carry out this study has been gathered through government publications, industry reports, and statistical yearbooks. Some of the important sources of data are the China Information Yearbook, China Statistical Yearbook, China Information Industry Yearbook, and provincial statistic yearbooks of each of the 11 provinces in the Yangtze River Economic Belt. The data is from 2011 to 2021, which offers one decade of analysis based on the development of digital transformation in the construction industry.

The most important variables in the data collection are correlated with the main dimensions of the digital transformation, which are; digital infrastructure, digital investment, digital applications, and sustainable development. These variables give a clear picture of the technological preparedness, investment, and output of the digital transformation activities in the provinces.

3.1.1 Data Sources

The empirical analysis in this study draws upon secondary data obtained from authoritative governmental and statistical publications. The primary data sources encompass the China Information Yearbook (2012-2022), the China Statistical Yearbook (2012-2022), the China Information Industry Yearbook (2012-2022), the China Construction Yearbook and the provincial statistical yearbooks of all 11 provinces and municipalities within the Yangtze River Economic Belt. These sources were selected for their comprehensive coverage, methodological consistency, and official recognition as reliable statistical references in the Chinese context.

The dataset spans an eleven-year period from 2011 to 2021, providing a robust longitudinal foundation for analyzing temporal trends in digital transformation. The geographic scope encompasses the entire Yangtze River Economic Belt, comprising 11 provincial-level administrative divisions, which are stratified into three sub-regions based on their geographic position along the river: the downstream region (Shanghai Municipality, Jiangsu Province, Zhejiang Province, and Anhui Province), the midstream region (Jiangxi Province, Hubei Province, and Hunan Province), and the upstream region (Chongqing Municipality, Sichuan Province, Guizhou Province, and Yunnan Province).

This stratification aligns with the established economic and developmental gradient observed across the YREB, wherein the downstream coastal provinces exhibit the highest levels of economic development and technological sophistication, the midstream provinces occupy an intermediate position, and the upstream inland provinces demonstrate relatively lower developmental indicators. This tripartite classification facilitates a nuanced comparative analysis of regional disparities in digital transformation, enabling the identification of distinct challenges and opportunities confronting each sub-region, and thereby supporting the formulation of targeted policy interventions tailored to the specific conditions of each area.

3.1.2 Sample CompositionThe complete datasets comprises 1,089 observations, derived from 11 provinces across 11 years, with nine indicator variables spanning four analytical dimensions. Table 2 presents a comprehensive breakdown of the sample composition.

Table 1: Sample Composition and Data Points

Dimension	No. of Indicators	Temporal Coverage	Total Data Points
Digital infrastructure	4	2011-2021	484
Digital investment	3	2011-2021	363
Digital application	2	2011-2021	242
Green development	2	2011-2021	242
Total			1331

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3.1.3 Data Collection and Validation

A rigorous and systematic data collection protocol was implemented to ensure data integrity and reprehensibility. The process commenced with the extraction of annual statistical yearbooks from official governmental databases maintained by the National Bureau of Statistics of China and provincial statistical bureaus, from which provincial-level indicator values for each of the 11 administrative divisions were meticulously recorded. Following extraction, all data entries underwent comprehensive verification, wherein provincial aggregates were cross-checked against corresponding national-level figures to ensure consistency; any discrepancies identified were resolved through direct reference to the original source documents. Missing data, constituting less than 5% of the total dataset, was addressed through linear interpolation methods, an approach justified by the minimal proportion of missing observations and the temporal continuity of the variables under investigation. Additionally, the Interquartile Range (IQR) method was employed to systematically identify and review statistical outliers; each outlier was examined individually, and where data entry errors were confirmed, appropriate corrections were implemented through source verification.

To ensure the reliability and validity of the collected data, multiple quality assurance measures were implemented. Triangulation of data sources was achieved by cross-validating key indicators against both provincial and national yearbooks, with national-level figures preferred in instances of discrepancy due to their standardized reporting methodology. Inter-rater reliability was assessed by having two trained research assistants independently extract a random sample comprising 20% of the total datasets, yielding an agreement rate of 98%, which indicates a high degree of reliability in the extraction process. Temporal consistency verification was conducted by examining time-series data for logical coherence, subjecting any unexpected year-on-year fluctuations to additional scrutiny and source verification. Finally, methodological transparency was ensured through the comprehensive documentation of all extraction protocols—including specific yearbook editions, page references, and extraction dates—in an appendix to the supplementary materials, thereby guaranteeing the full reprehensibility of the research.

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3.2 Evaluation Index System

3.2.1 Theoretical Foundations

The evaluation index system developed in this study is grounded in the established literature on digital transformation assessment and has been contextualized to the specific characteristics of China's construction industry. Building upon prior research by Zhang et al. (2023), Chen (2023), and Chmeit et al. (2024), the system operationalizes digital transformation through four core dimensions, each capturing a distinct facet of the digitalization phenomenon.

The selection of indicators followed three main criteria: (1) theoretical relevance, meaning that each indicator must have a clear conceptual link to digital transformation in the construction industry as supported by the existing literature; (2) data availability, requiring that the indicators be consistently available for all 11 provinces over the 2011–2021 period to ensure full coverage and enable longitudinal analysis; and (3) measurement validity, meaning that each indicator should be widely used and validated in prior empirical studies on digital transformation so that the results can be meaningfully compared with existing research.

3.2.2 Operational Definitions

The index system is organized into four primary dimensions, each composed of multiple secondary indicators:

- **Digital Infrastructure (Weighted 0.321):** This dimension relates to the preparedness of technological infrastructure, including the availability of broadband internet and mobile communication base stations and optical fiber cable networks. Successful digital transformation in the construction industry is a prerequisite for the quality of digital infrastructure.This dimension reflects the technological readiness of each province’s digital ecosystem and serves as the basic layer supporting digital transformation. The following proxy indicators are used: (1) Broadband Internet Access Ports (per 100 persons), which captures the density of fixed broadband connections and thus reflects the availability of high-speed internet infrastructure necessary for cloud-based construction technologies; (2) Mobile Communication Base Stations (per 1,000 persons), which measures the coverage of cellular networks and is important for deploying IoT-enabled construction site monitoring systems; and (3) Optical Fiber Cable Length (km per km²), which represents the physical scale of fiber-optic networks and indicates the backbone capacity for data transmission required by more advanced digital applications.

- **Digital Investment (Weighted 0.241):** This dimension reflects the financial commitment to digitalization initiatives and indicates the level of capital allocation toward technological adoption. The following proxy indicators are employed: (1) E-commerce Transaction Enterprises (Proportion of Total, %), which measures the extent to which firms have integrated digital platforms into their operations and serves as a proxy for digital business readiness and the broader penetration of digital commerce capabilities; (2) Research and Development (R&D) Expenditure Intensity (% of GDP), which captures the overall investment in innovation activities and reflects the regional prioritization of technological advancement and knowledge creation; and (3) High-Technology Enterprises in Construction (Proportion of Total, %), which specifically measures the presence of technology-oriented firms within the construction sector and indicates the industry-level digitalization capacity and propensity to adopt advanced construction technologies. Collectively, these indicators provide a comprehensive assessment of the financial and institutional investments underpinning digital transformation in the construction industry.
- **Digital Applications (Weighted 0.267):** This dimension measures the practical implementation of digital technologies in construction operations and is operationalized through two proxy indicators: (1) Digital Technology Patent Applications (Cumulative Count), which reflects the generation of technological innovations in construction-related digital technologies and serves as a measure of inventive activity and the sector's capacity for technological development; and (2) Employees Trained in Digital Tools (BIM, IoT, AI) (Per 1,000 Workers), which captures the supply of digitally skilled labor and is essential for the effective deployment of advanced construction technologies, as the availability of trained personnel directly influences the successful adoption and utilization of digital systems. Together, these indicators provide a comprehensive assessment of both the innovative output and human capital readiness that underpin the practical implementation of digital transformation in the construction industry.

- **Green Development (Weighted 0.180):** This dimension assesses the environmental outcomes associated with digital transformation and is operationalized through two proxy indicators: (1) CO_2 Emissions per Unit of Construction Output (Tons per Million RMB) , which measures the environmental impact of construction activities, with lower values indicating more sustainable practices and greater environmental performance in the production process; and (2) Energy Consumption per Unit of Construction Output (kWh per Million RMB) , which captures resource efficiency in construction operations and represents a key sustainability outcome, as reduced energy intensity reflects improved operational efficiency and diminished environmental footprint. Together, these indicators provide a comprehensive assessment of the environmental implications of digital transformation, enabling the evaluation of whether technological advancement contributes to the decoupling of construction activity from environmental degradation.

Using a thorough analysis of the available literature and based on the principles of industrial transformation and upgrading, this paper evaluates the degree of transformation and upgrading in the construction industry under four main aspects: digital infrastructure, digital applications, digital investment, and sustainable development. Table 2 shows the particular evaluation indicators.

Table 2 Digital Transformation Evaluation Index

Primary index	Secondary index	Variables	Attribute
Comprehensive digital transformation index	Digital infrastructure	Number of broadband internet access ports.	Positive
		Number of mobile communication base stations.	Positive
		Length of optical fiber cable lines.	Positive
		Proportion of enterprises engaged In E-commerce transactions.	Positive
	Digital investment	R&D expenditure intensity.	Positive
		Share of High-Tech enterprises in CI.	Positive
		Software investment In the CI.	Positive
	Digital application	Number of patent applications.	Positive
		Number of digital technology personnel in the CI.	Positive
	Green development	CO_2 emission.	Negative
		Energy consumption per unit of construction output.	Negative

3.3 Research Method

3.3.1 Analytical Approach

The Entropy-Weight Method (EWM) was selected as the principal analytical technique for constructing the composite digital transformation index, a methodological choice justified on three grounds. First, EWM constitutes an objective weighting method that determines indicator weights based on the inherent information content of the data, thereby circumventing the subjectivity inherent in expert weighting or equal-weighting approaches (Shannon, 1948; Chen et al., 2014). This objectivity is particularly valuable in the context of provincial-level comparative analysis, where subjective biases could otherwise distort regional rankings and compromise the validity of cross-sectional comparisons. Second, EWM is well-suited to multi-indicator systems characterized by diverse measurement units, as the normalization process standardizes disparate indicators onto a common scale without imposing restrictive distributional assumptions (Hwang & Yoon, 1981), thus accommodating the varied nature of the indicators employed in this study. Third, EWM has been extensively validated in prior empirical studies examining technology adoption and regional development disparities (Zhang et al., 2020; Liu et al., 2021), demonstrating its robustness and reliability for analytical contexts similar to that of the present investigation. Collectively, these justifications establish EWM as an appropriate and defensible methodological foundation for assessing digital transformation across the YREB provinces.The most essential stages of analysis are as follows:

1. **Normalization of Data:** Before analyzing the data, the raw data of each indicator was normalized to remove the impact of dimensional variations. The normalization process guarantees the alignment of the data of all indicators into a similar

$$Z_{tij} = \frac{X_{tij} - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

$$Z_{tij} = \frac{X_{\max} - X_{tij}}{X_{\max} - X_{\min}} \tag{2}$$

Where Z_{tij} normalized value of indicator j for Province i, X_{ij} is the original value of indicator j for province i and $X_{\min}$ and $X_{\max}$ is the Minimum and Maximum Values of indicator j across all provinces.

2. **Calculation of Entropy Weights:** The entropy weight of each indicator was calculated to determine its importance in the overall evaluation. Indicators with greater variability (i.e., those that show more differentiation between provinces) are assigned higher weights. The entropy of each indicator j is calculated as follows:

$$P_{tij} = \frac{Z_{tij}}{\sum_{t=1}^{11}\sum_{t=i}^{11} Z_{tij}} \tag{3}$$

$$E_j = -k\sum_{t=1}^{11}\sum_{i=1}^{11} Z_{tij} \tag{4}$$

Which, $$k = \frac{1}{\ln(t \times i)}$$

$$D_j = 1 - E_j \tag{5}$$

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$$W_j = \frac{D_j}{E\sum_{j=1}^{n} D_j} \tag{6}$$

Where: P_{tij} is the Probability or normalized weight for indicator j in province i at year t, Z_{tij} normalized value of indicator j for province i at year t, E_j is the Entropy of the indicator j, D_j was used to calculate the redundancy and W_j was later used to assign weight for each indicator.

3. **Composite Score Calculation:** The final composite digital transformation index for each province-year observation was calculated by aggregating the weighted values of each indicator. The composite score reflects the overall level of digital transformation in each province, considering all four dimensions of infrastructure, investment, applications, and sustainability.

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$$V_{ti} = P_{tij} \times W_j \tag{7}$$

Where: V_{ti} means the final composition score, P_{tij} is the probability or normalized weight and W_j is the weight for each indicator.

4. Data Analysis and Interpretation

The geographical composition of China is clearly gradual in the eastern direction towards the west, with the same trend copied not just in the various physical landscapes of the country but also in economic, demographic, and industrial aspects. This gradient is observed in the striking differences between the high population density of the coastal areas in the east and the less densely populated and less developed western provinces. Such differences play a pivotal role in comprehending how different industries, especially the construction industry, are being digitally transformed in China.This east-west gradient is further demonstrated by the Yangtze River Economic Belt, which is one of the most important economic belts in China. It cuts across a number of provinces, and sub-regions are defined by their geographical positioning along the river. The provinces may be divided into three major sub-regions depending on their location with reference to the river: the upstream (or upper) section, the midstream section, and the downstream (or lower) section.To provide a more comprehensive analysis of the spatial variation of the digital transformation in the construction industry, we define these sub-regions in this research paper. Through the analysis of the economic growth, the industrial status, and the digital infrastructure in the upper, middle, and lower parts of the Yangtze River, we are going to figure out how these regions are different in terms of their use of digital technologies and innovative practices.The following map (below) graphically depicts the Yangtze River Economic Belt and how it has been divided into upper, middle, and lower parts, and it provides a good representation of the geographical distribution and the differing levels of digital transformation of these areas.[Insert Image: Map of the Yangtze River Economical Belt with the sub-regions.

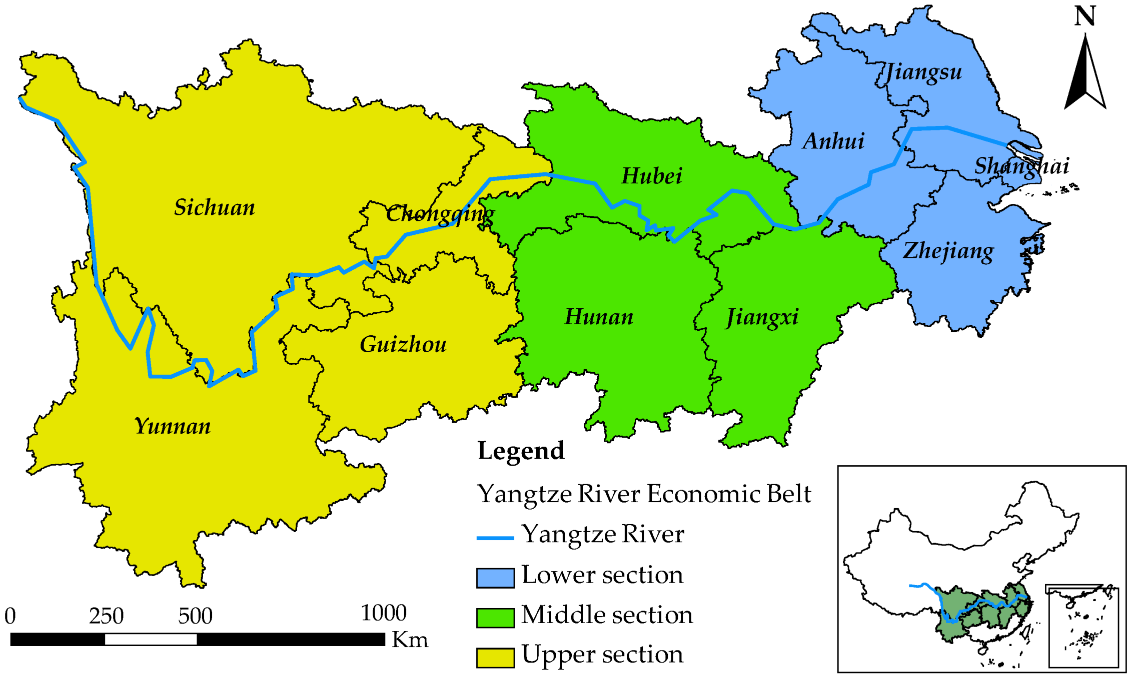

Fig.1 Regional Distribution Map

4.1 Overview of Digital Transformation Score

The overall trend of digital transformation in the YREB from 2011 to 2021 shows gradual progress, but with clear differences between the upstream, midstream, and downstream sub-regions. The downstream region consistently shows the highest levels of digital transformation, while the upstream and midstream regions face more significant challenges.

Table 3: gives the comprehensive digital transformation Scores of the construction industry in these regions between 2011 and 2021.

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Table 3: Comprehensive Score of Digital Transformation Level

Year	Entire region	Upstream	Midstream	Downstream
2011	0.234	0.183	0.212	0.303
2012	0.265	0.212	0.236	0.339
2013	0.289	0.238	0.255	0.364
2014	0.148	0.096	0.142	0.205
2015	0.169	0.117	0.158	0.229
2016	0.186	0.135	0.173	0.246
2017	0.194	0.141	0.178	0.260
2018	0.207	0.151	0.189	0.277
2019	0.215	0.157	0.195	0.288
2020	0.228	0.168	0.206	0.303
2021	0.238	0.176	0.210	0.320
Average	0.216	0.161	0.196	0.285

The digital transformation of the construction industry in the Yangtze River Economic Belt (YREB) reveals significant regional differences in the adoption of advanced technologies. To provide an overview of the digital transformation across the provinces, Figure 3-1 presents the digital transformation index for each of the 11 provinces in the YREB. The chart clearly shows the disparities in digital adoption, with some provinces like Jiangsu, Shanghai, and Zhejiang exhibiting much higher digital transformation indices compared to others like Guizhou and Yunnan.

The chart provides an essential starting point for understanding the extent of digital transformation before analyzing the specific conditions and trends in the upstream, midstream, and downstream regions.

- Jiangsu (0.338) and Shanghai (0.312) have the highest digital transformation indices. This is because they have better infrastructure and more people using technologies like BIM, IoT, and AI.
- Guizhou (0.112) and Yunnan (0.113), on the other hand, exhibit much lower scores, indicating the challenges these provinces face in adopting digital technologies in their construction industries.

With this broad overview, we now turn to a more detailed analysis of the upstream, midstream, and downstream regions to explore the specific factors contributing to these differences.

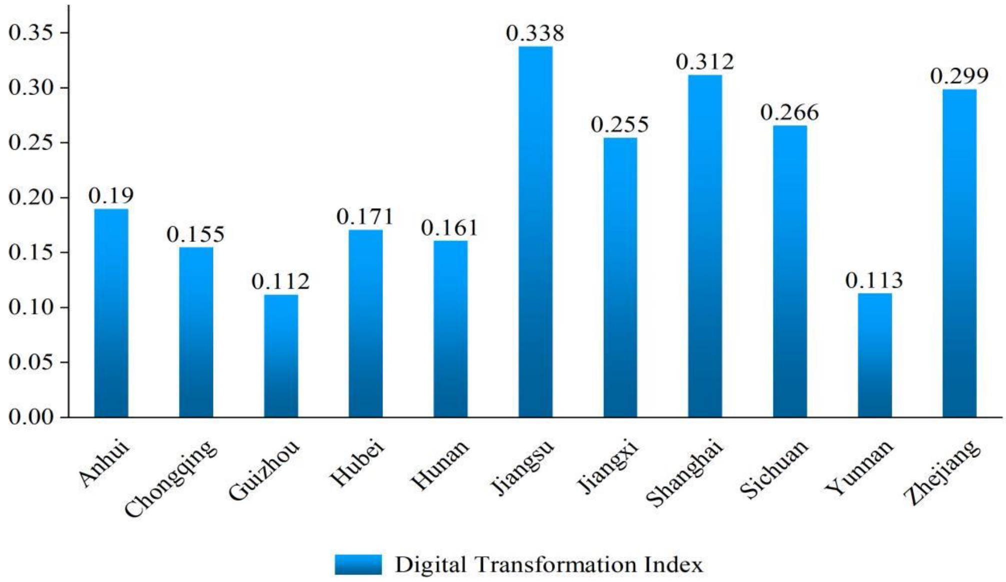

Fig. 2 Average Digital Transformation Index of All Provinces (2011-2021)

4.2 Upstream Region: Challenges in Digital Transformation

The upstream region, comprising the Sichuan, Chongqing, Guizhou, and Yunnan provinces, has the biggest difficulties regarding digital transformation. It is the provinces of low economic development, low technological infrastructure, and inability to invest in digital technologies.

- In 2021, the upstream region had the lowest average digital transformation index of 0.161. Sichuan scored the best in this region with 0.266, indicating some improvement in the use of digital. Nevertheless, such provinces as Guizhou (0.122) and Yunnan (0.113) are way behind.
- The better score in Sichuan can be explained by the fact that the region has an industrial background and certain advancements in digital infrastructure; however, the province continues to still experience such problems as poor connectivity, access to high-level digital technologies and applications such as BIM, IoT, and AI, and a lack of skilled employees.

- The provinces of Guizhou and Yunnan have lower scores and are characterized by a strong digital gap, as they are slowed down by less developed technological infrastructure, less industry, and reduced investments in digital tools.

In general, the slower rate of the digital transformation in the upstream region can be mostly attributed to the economic reasons, inadequate digital infrastructure, and lack of workforce training. These are issues that will be important in enhancing the digital adoption in this sub-region.

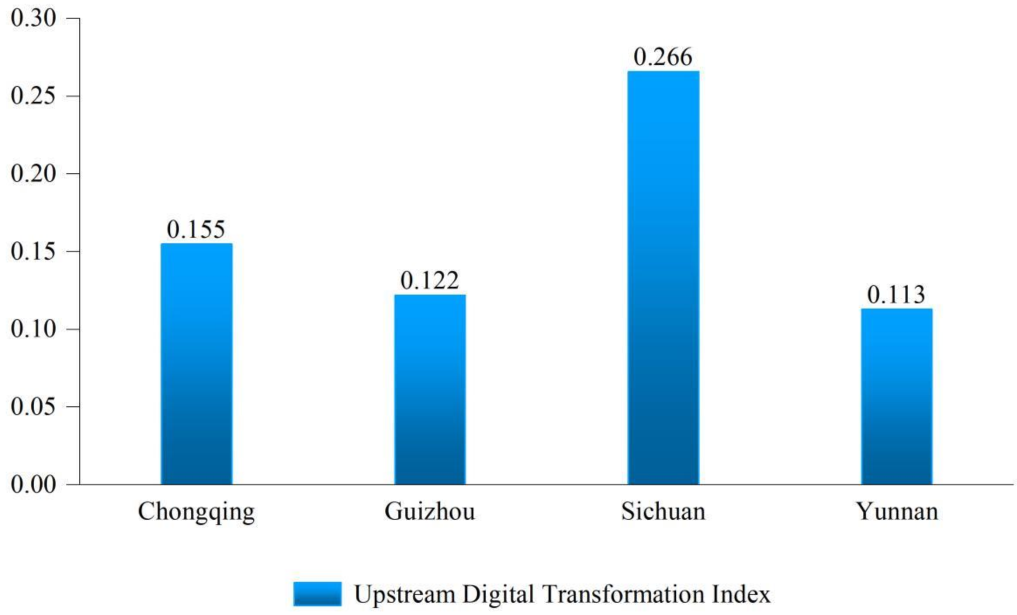

Fig. 3 Average Digital Transformation Index -- Upstream Region (2011-2021)

4.3 Midstream Region: Slow but Constant Progress.

The midstream region encompassing provinces like Jiangxi, Hubei, and Hunan has more moderate tendencies of digital transformation. Although these provinces demonstrate a gradual improvement, they continue to struggle with the problems of infrastructure, investments, and the presence of a workforce.

- The midstream has a mean digital transformation index of 0.196 in 2021, which is higher than upstream but still lower than downstream. Jiangxi scored the highest in the region, with the value being 0.255, which indicates the greater dedication to digital transformation.
- Hubei (0.171) and Hunan (0.161) demonstrate rather low scores, which means that these provinces still have significant impediments, including the lack of

infrastructure and available funding to implement digital projects and employ qualified professionals that will work with modern digital tools.

Nevertheless, under these circumstances, the midstream region is undergoing a more balanced and slower process of digital transformation. This movement indicates that, although the pace of adoption of digital is on an upward trend, it is not as high as in the downstream region.The development of the midstream region is limited due to the lack of digital technology usage, economic constraints, and the workforce skills disparity in the region. Nevertheless, the more balanced development of the midstream region compared to the upstream region indicates that specific interventions can significantly accelerate digital transformation.

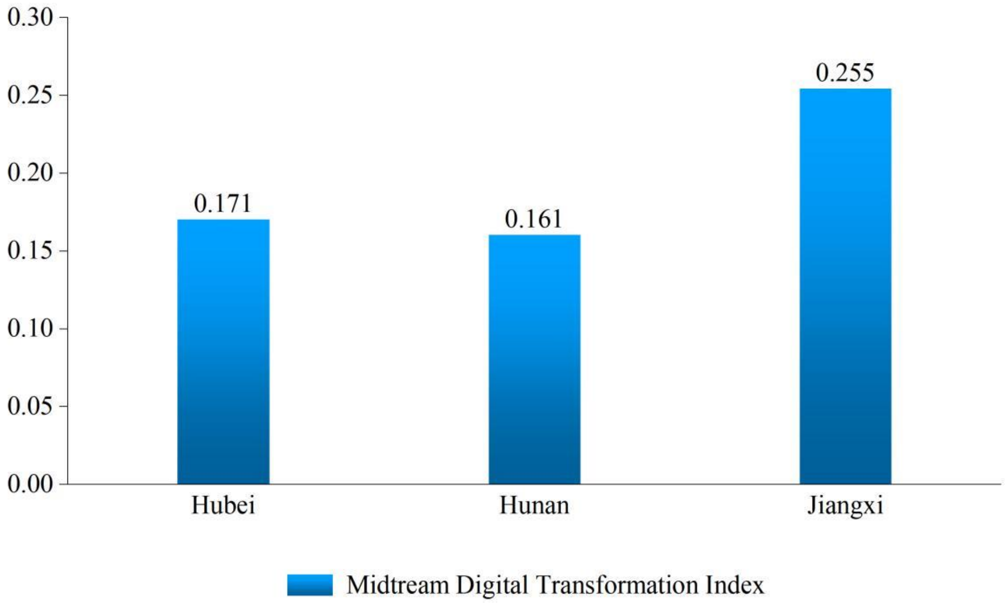

Fig. 4 Average Digital Transformation Index -- Midstream Region (2011-2021)

4.3 Downstream Region: Digital Revolution in the Lead

Most developed in digital transformation is the downstream region comprising provinces such as Jiangsu, Shanghai, and Zhejiang. These provinces enjoy good infrastructure, good economic resources, and more investment in digital technologies.

- In 2021, the downstream regional index of digital transformation stood at 0.285, which is the largest among them all. Jiangsu is first with the index of 0.338, and then Shanghai (0.312) and Zhejiang (0.299) with an index that is much higher than the regional index.
- This excellent performance of the downstream region can be attributed to the well-established digital infrastructure, a high degree of investment in research and

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development, and the well-established industrial ecosystem. It is also useful to the region because it is close to world markets, which allows it to implement the latest technologies, such as BIM, IoT, and AI.

- The difference in the lowest and the highest provincial scores in the downstream region is 0.148, which shows that there are some internal imbalances, but at the same time, the level of digital maturity is relatively high as compared to the upstream and midstream regions.

The success of the downstream region is supported by sound economic backgrounds, big investment in digital technologies, and established digital infrastructures. These aspects have enabled the region to be the leader in the digital transformation of the construction industry.

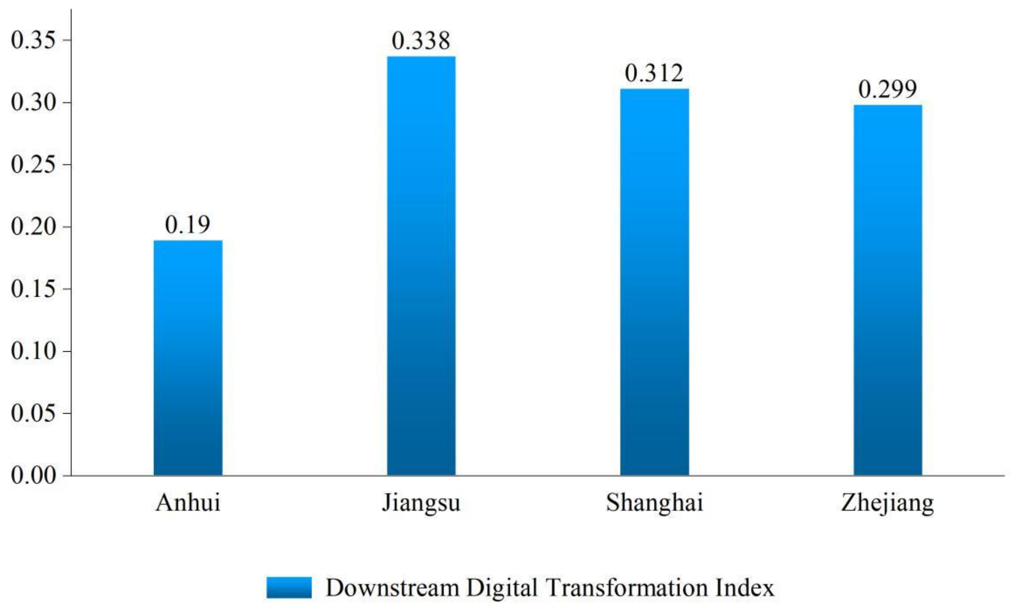

Fig. 5 Average Digital Transformation Index - Downstream Region (2011-2021)

4.5. Regional Trends and Implications

General Regional Trend: Figure 6 illustrates that overall there is an evident east-west extent of digital transformation through the YREB. The digital adoption is still led by the downstream region with its greater levels of development. On the contrary, the upstream and midstream regions are underperforming, with a mix of economic difficulties, bad infrastructure, and skilled labor deficiency.

Gap Analysis: The digital transformation gap between the downstream and upstream regions is still huge, and the gap between the highest and the lowest provincial scores has been 0.226 in 2021. This explains why specific investments and policies are necessary that would help minimize the difference between the regions.

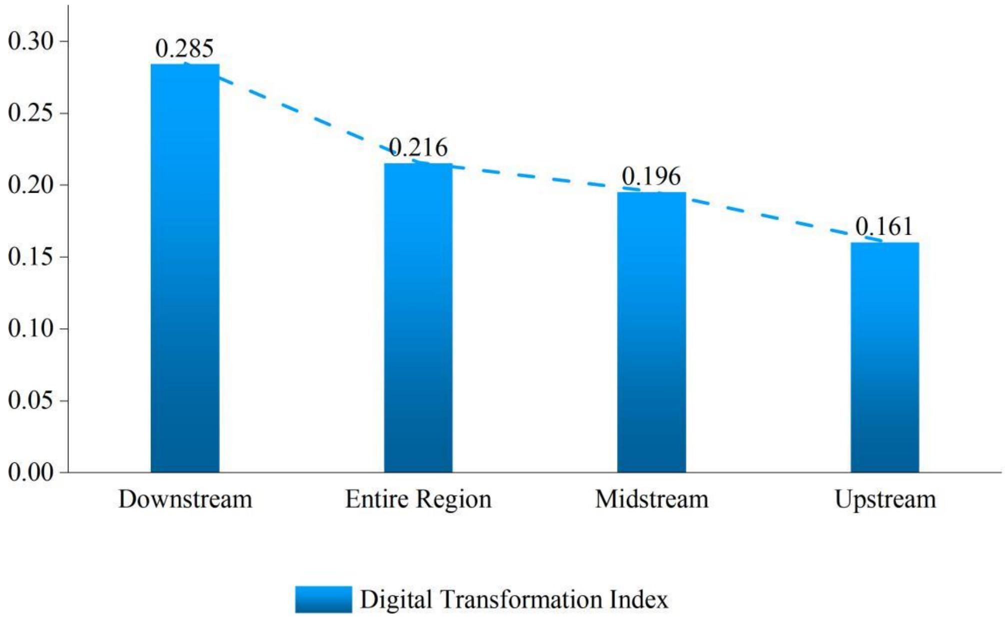

Fig.6 Average Digital Transformation Index-Entire Region and Three Sub-regions (2011-2021)

5. Research Contribution and Policy Recommendation

5.1 Novel Contributions and Implications

5.1.2 Theoretical Contributions

This study makes three significant theoretical contributions to the scholarly literature on digital transformation in the construction industry. First, it extends the Technology-Organization-Environment (TOE) framework to the regional analysis of digital transformation, demonstrating that regional heterogeneity in technology adoption can be systematically explained through the lens of technology readiness (digital infrastructure), organizational capacity (investment and skills), and environmental conditions (economic development and policy support). The empirical findings reveal that the downstream region's superior digital transformation performance is attributable to favorable conditions across all three TOE dimensions advanced technology infrastructure, high organizational investment, and supportive economic-environmental conditions while the upstream region's lagging performance is characterized by constraints across all dimensions, including limited technology infrastructure, insufficient organizational capacity, and less favorable environmental conditions. The midstream region occupies an intermediate position, with moderate conditions across the TOE dimensions and consequently moderate digital transformation outcomes. This theoretical extension contributes to the broader literature on technology diffusion by demonstrating the applicability of organizational adoption frameworks to the spatial analysis of technology deployment, thereby bridging a gap between organization-level adoption theories and regional-level diffusion studies.

Second, this study provides robust empirical evidence of persistent digital divides within the construction industry of a major economic region. The documentation of a 0.226 gap between the highest and lowest provincial scores, maintained over a decade, contributes to the growing literature on spatial inequality in technology adoption. Importantly, the finding that regional disparities have not diminished over time challenges the conventional assumption that digital transformation naturally diffuses from more developed to less developed regions through trickle-down effects, suggesting instead that targeted interventions are required to bridge the digital divide and that market forces alone are insufficient to ensure equitable technology diffusion.

Third, by operationalizing digital transformation through four distinct dimensions infrastructure, investment, applications, and sustainability the study demonstrates that digitalization is a multi-faceted phenomenon that cannot be captured through single-technology or single-dimension assessments. This conceptualization contributes to a more nuanced understanding of digital transformation as an ecosystem of interrelated components rather than a binary adoption status, thereby enriching the theoretical discourse on how digital transformation should be conceptualized and measured in the construction industry context.

5.1.3 Methodological Contribution

The study advances methodological knowledge in three important ways. The evaluation index system developed in this study represents a validated instrument for assessing digital transformation in the construction industry at the regional level; the framework's theoretical grounding, empirical validation, and demonstrated robustness across sensitivity analyses establish its credibility as a reliable tool for future research applications. Furthermore, the comprehensive dataset compiled for this study, spanning 11 provinces across 11 years with nine indicators, constitutes a valuable resource for the scholarly community, supporting replication studies, extension analyses, and future comparative research that may examine digital transformation trends beyond the 2011-2021 period or explore additional dimensions of digitalization. Finally, the systematic methodology encompassing data collection, normalization, weighting, and score calculation is explicitly documented to facilitate replication in other contexts; researchers examining digital transformation in other economic regions, such as the Pearl River Delta or the Beijing-Tianjin-Hebei region, can readily adapt this methodology for comparative purposes, thereby enabling a broader understanding of regional digital transformation patterns across China and potentially in other national contexts.

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5.2 Policy Recommendations

- Investment in Digital Infrastructure: To address the digital gap, especially in the upstream and midstream regions, significant investments in digital infrastructure--such as high-speed internet, mobile networks, and optical fiber networks--are essential to enable the adoption of advanced technologies like BIM and IoT.
- Workforce Development: The lack of a digitally skilled workforce in the upstream and midstream regions is a significant barrier to digital adoption. Establishing targeted training programs and partnerships with educational institutions will help bridge the skills gap and equip workers with the capabilities needed to implement and manage digital technologies.
- Financial Incentives for SMEs: Many small and medium-sized enterprises (SMEs) in the upstream and midstream regions are hesitant to adopt digital technologies due to the high initial costs. Policymakers should consider providing financial incentives, subsidies, or low-interest loans to SMEs to ease the financial burden and encourage the adoption of digital tools.
- Government Support and Policy Frameworks: Government initiatives that encourage digital adoption, such as tax incentives, grants, and dedicated support programs for digital transformation, can significantly accelerate the process, particularly in underdeveloped regions.

5.3 Future Research Directions

While this study provides a snapshot of digital transformation in the YREB, further research is needed to explore the long-term effects of digital adoption on the construction industry's productivity, sustainability, and cost-efficiency. Future studies could also investigate the role of specific digital tools in improving project outcomes and explore the impact of digital transformation on environmental sustainability in the construction sector.

In conclusion, while progress has been made in the digital transformation of the construction industry in the YREB, a more balanced and integrated approach is needed to ensure that all regions can fully realize the potential of digital technologies. Targeted investments, policies, and workforce development initiatives are key to ensuring that the benefits of digital transformation are shared across the entire region.

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