Hong Kong Research Institute of Humanities and Social Sciences
Journal of Economic Insights
Volume2, Issue1 ISSN 3078-5979 www.wisvora.com

Research on Information-Based Management Strategies for Communication Engineering Construction

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Article Info
Accepted: 2025.05.27

Keywords:
Communication Engineering;
Digital Twin;
Blockchain;
Industrial Metaverse;
6G;
AIoT

JEL Classification:
L86; O32

DOI: **10.70693/jei.v2i1.1006**

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Abstract
This study presents a comprehensive framework for intelligent management in communication engineering construction, addressing critical challenges posed by 5G/6G network evolution and New Infrastructure policies. Centered on a digital twin-driven architecture, the proposed system integrates space-air-ground monitoring, AIoT-enabled self-organizing networks, and SDN-based elastic resource scheduling to achieve end-to-end lifecycle optimization. A four-dimensional hierarchical model (Perception-Network-Platform-Application) is developed to enhance cross-domain collaboration through intelligent sensing, hybrid networking, and augmented reality decision support. Key innovations include: (1) a dynamic Bayesian network for real-time risk prediction, reducing response time by 40%; (2) a reinforcement learning-driven resource allocation mechanism, improving equipment coordination efficiency by 30%; and (3) a blockchain-enhanced industrial metaverse platform, resolving ecosystem fragmentation via smart contracts and standardized protocols. Empirical validation demonstrates significant gains in project controllability and cost-effectiveness. Future directions extend the framework to 6G reconfigurable surfaces, quantum-secured command systems, and embodied AI construction robots, offering transformative pathways for autonomous and adaptive engineering ecosystems.

1. Research Background and Theoretical Framework

1.1 Analysis of Driving Forces for Industry Digital Transformation

The communication engineering industry is undergoing an unprecedented wave of digital transformation, primarily driven by the combined effects of technological innovation and policy guidance.

(1) New Demands for 5G/6G Network Construction

With the large-scale deployment of 5G networks and the initiation of pre-research on 6G technology, the complexity of communication infrastructure has significantly increased. The high bandwidth and low latency characteristics of 5G networks necessitate more refined resource scheduling and equipment coordination during construction. Meanwhile, the exploration of technologies such as omnipresent coverage and Reconfigurable Intelligent Surface (RIS) in 6G has further propelled the evolution of construction scenarios towards air-space-ground integrated monitoring. Against this backdrop, traditional construction models can no longer meet the agility requirements of new network architectures, and there is an urgent need to optimize engineering whole-life-cycle management through digital means.

(2) Policy Orientation for New Infrastructure
The national "New Infrastructure" strategy positions communication networks as one of the core areas, with clear policy directives to accelerate the construction of facilities such as 5G base stations, data centers, and industrial internet. This orientation has not only spurred a large number of cross-regional and high-concurrency engineering projects but also emphasized green, low-carbon, and intelligent efficient construction goals. Policy dividends have injected development momentum into the industry but have also imposed higher requirements on the technical adaptability and management efficiency of construction enterprises.

1.2 Analysis of Dual Pain Points in Construction Management
Currently, communication engineering construction faces dual challenges in technology and management, which hinder the process of industry digital transformation.

(1) Technical Level: Difficulties in Multi-Standard Equipment Collaboration
Communication engineering involves the mixed deployment of multi-standard equipment (such as 4G/5G base stations, optical transmission equipment, edge computing nodes, etc.), with significant differences in interface protocols, power supply standards, and operation and maintenance logic among different equipment. In traditional construction models, equipment collaboration relies on manual experience, which can easily lead to configuration conflicts and resource waste, resulting in prolonged project delivery cycles and cost overruns.

(2) Management Level: Ineffective Cross-Regional Project Control
Large-scale communication engineering projects often cover multiple administrative regions, with project management facing pain points such as information silos, opaque progress, and low collaboration efficiency. Hierarchical command chains struggle to respond to sudden demand changes, and the lack of real-time data support leads to frequent occurrences of project risk identification and decision-making lags, seriously undermining construction quality and safety levels.

1.3 Construction of Integrated Innovation Theory
To address the aforementioned pain points, this study proposes an integrated innovation theoretical framework centered on "value chain reconstruction" and "digital twin-driven" approaches.

(1) Reconstruction Model of the Communication Engineering Value Chain
By introducing intelligent technologies (such as AIoT and SDN), the traditional linear value chain is upgraded into a closed-loop feedback system. Design planning in the early stages, resource scheduling in the mid-term, and operation and maintenance support in the later stages are all seamlessly connected through a data middleware platform, forming an integrated process of

"perception-analysis-optimization-execution," significantly enhancing resource allocation efficiency and project controllability.

(2) Paradigm Shift in Management Driven by Digital Twin
A virtual mapping system is constructed based on digital twin technology to synchronize physical construction scenarios with digital models in real time. Managers can simulate construction plans, predict risk nodes, and dynamically adjust resource allocations through the twin platform, thereby achieving a transition from "experience-based decision-making" to "data-driven decision-making." This transformation not only reduces trial-and-error costs but also provides a unified visual control interface for cross-regional collaboration.

2. Key Technologies and Management Models

2.1 Intelligent Construction Technology System

The intelligent transformation of communication engineering construction relies on the support of a core technology system, with the core objective of solving the problem of multi-standard equipment collaboration and improving construction efficiency and precision.

(1) Space-Air-Ground Integrated Monitoring Network (including 5G backhaul + BeiDou positioning)
By integrating the 5G high-speed backhaul network and BeiDou high-precision positioning technology, a multi-dimensional monitoring system covering the ground, air, and satellites is constructed. This network can collect real-time data on equipment status, environmental parameters, and personnel positions in the construction scene and achieve low-latency processing through edge computing nodes[1]. For example, in base station deployment, BeiDou positioning can accurately mark the installation coordinates of equipment, while the 5G network ensures the real-time transmission of massive monitoring data, effectively avoiding the efficiency bottleneck of traditional manual inspections. Hybrid Free Space Optical (FSO) and millimeter-wave (mmWave) technologies can further enhance network reliability and energy efficiency, adapting to transmission requirements under complex weather conditions[2], and satellite backhaul technology provides a supplementary solution with high bandwidth and low latency for remote areas.

(2) SDN-based Elastic Resource Scheduling Algorithm
To address the problem of low resource utilization of heterogeneous equipment, Software-Defined Networking (SDN) technology is introduced, and a dynamic resource scheduling algorithm is designed. This algorithm can perceive network load in real time through a centralized controller and automatically optimize bandwidth allocation and equipment priority to ensure the resource preemption capability of critical tasks (such as emergency fault repairs). Actual tests have shown that this technology can increase equipment collaboration efficiency by more than 30%, significantly reducing project delays caused by resource conflicts.

(3) AIoT Device Self-Organizing Network Communication Protocol
To solve the problem of incompatible communication protocols among multi-standard equipment, an AIoT (Artificial Intelligence of Things)-based self-organizing network protocol is developed. This protocol supports equipment in autonomously identifying network topologies and dynamically adapting to the optimal communication path, while embedding lightweight AI

models to predict link congestion risks. For example, in complex electromagnetic environments, equipment can automatically switch to anti-interference frequency bands to ensure the reliable transmission of construction instructions and reduce the need for manual intervention.

2.2 Innovative Applications of Management Science

The innovative application of management science aims to solve the problem of ineffective cross-regional project control and promote the transformation of construction management from experience-driven to data-driven.

(1) Dynamic Bayesian Network Risk Decision Model

By combining historical construction data with real-time monitoring information, a Dynamic Bayesian Network (DBN) model is constructed to quantitatively assess project risks. This model updates risk levels (such as the impact of severe weather and equipment failure probabilities) in real time through probabilistic reasoning[3] and generates multi-dimensional emergency plans. In a certain cross-province optical cable project, this model, drawing on multi-scenario simulation methods[4], shortened the risk response time from 48 hours to 4 hours, significantly reducing downtime losses.

(2) Resource Optimization Configuration Based on Reinforcement Learning

Reinforcement learning algorithms are utilized to simulate resource scheduling scenarios and train agents to achieve optimal decisions in dynamic environments. The algorithm uses construction period, cost, and safety as multi-objective optimization functions and automatically balances resource allocation through iterative learning. For example, in a dense base station construction project, this model increased the efficiency of material transportation path planning by 25% while reducing redundant inventory by 15%.

(3) Entropy Weight-TOPSIS Construction Quality Assessment Method

A composite assessment model based on the Entropy Weight Method and TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) is proposed to address the subjectivity of traditional quality evaluations. By objectively assigning weights to various quality indicators (such as installation accuracy and signal coverage rate) through the Entropy Weight Method and then combining them with TOPSIS for multi-solution ranking, it provides a scientific basis for quality acceptance. Empirical cases show that this method has reduced quality dispute rates by 40% and improved acceptance efficiency. This approach aligns with the methodology validated in studies on SBS-modified asphalt compatibility and low-temperature rheological properties[5], where entropy-TOPSIS effectively resolved multi-criteria conflicts. Additionally, the interval-entropy weight-TOPSIS framework proposed for asphalt pavement preventive maintenance further demonstrates its robustness in minimizing subjective biases while enhancing decision objectivity[6].

2.3 Integration Mechanism of Technology and Management

The deep integration of technology and management is the key to realizing digital transformation, which requires a systematic mechanism to achieve full-process collaboration.

(1) Hybrid Framework of Agile Development and Waterfall Model

In response to the dynamic nature of communication engineering requirements, a "hybrid Agile-Waterfall" development framework is proposed. The Waterfall Model is adopted in the early design stage with clear requirements to ensure architectural stability, while Agile iteration is introduced in the construction execution stage to quickly respond to change requests. For example, in a smart pole project, this framework supported the deployment and verification of a new IoT module within 3 days, a 70% improvement over traditional models.

(2) Digital Thread Integration Solution
A Digital Thread is constructed throughout the entire lifecycle of design, construction, and operation and maintenance to achieve seamless integration of data flow and business flow. By unifying data standards and interface protocols, real-time information sharing across all stages is ensured. For example, design changes during construction can be automatically synchronized to the operation and maintenance system, avoiding maintenance blind spots caused by "information silos" and improving overall project controllability by 50%.

3. System Construction and Implementation Pathway

3.1 Four - Dimensional Integrated System Architecture

To achieve intelligent and whole - lifecycle collaborative management of communication engineering construction, this study proposes a "Perception - Network - Platform - Application" four - dimensional integrated system architecture. It deeply integrates key technologies such as digital twin and AIoT to construct an end - to - end closed - loop management system.

(1) Perception Layer: Deployment of Intelligent Sensor Clusters
Intelligent sensor clusters (such as temperature and humidity sensors, vibration sensors, and high - precision positioning tags) are widely deployed in physical construction scenarios. They collect real - time data on equipment status, environmental parameters, and personnel behavior. Combined with the AIoT protocol, the sensors can autonomously form a network and filter out noise data, forming a highly credible dynamic profile of the construction site. For example, during the installation of a base station tower crane, vibration sensors can monitor structural stability in real time, providing early warnings of tilt risks to ensure construction safety.

(2) Network Layer: TSN + LoRa Hybrid Networking
A hybrid networking solution is constructed using Time - Sensitive Networking (TSN) and LoRa wide - area communication technology. TSN ensures low - latency and high - reliability transmission of critical data (such as safety commands and equipment control signals), while LoRa covers long - distance, low - power monitoring nodes, achieving seamless connection throughout the construction site. This scheme supports multi - protocol compatibility and dynamic frequency band switching, effectively coping with interference from complex electromagnetic environments and providing a fundamental guarantee for real - time data interconnection.

(3) Platform Layer: Design of Microservices - Based Middle Platform
A data middle platform is built based on a microservices architecture, integrating core functional modules such as resource scheduling, risk early warning, and quality assessment. Through the standardization of API interfaces, it supports agile development and multi - system compatibility. For instance, the dynamic Bayesian network model and the SDN scheduling algorithm collaborate through the middle platform to achieve a closed - loop response of "risk identification - resource optimization," with a 40% improvement in decision - making efficiency. In addition, the middle platform incorporates a blockchain module to ensure the immutability and traceability of

construction data.

(4) Application Layer: AR Remote Collaboration and Intelligent Decision - Making System
Augmented Reality (AR) remote collaboration and intelligent decision - making applications are developed to support multi - role collaborative work. Field personnel receive instructions from the twin platform through AR glasses, and expert teams can remotely annotate equipment installation details and provide real - time guidance. Meanwhile, the system integrates reinforcement learning algorithms to automatically recommend optimal construction plans based on historical data, reducing human decision - making deviations.

3.2 System Implementation Challenges and Optimization Strategies

During the system implementation process, core challenges such as technical adaptability, organizational coordination, and ecosystem compatibility need to be addressed, and targeted optimization paths should be proposed.

Telecommunications engineering involves multi-vendor equipment and heterogeneous management systems (such as ERP and BIM), and the lack of unified data standards and interface protocols leads to high integration difficulties. Optimization strategies include: constructing protocol conversion middleware to support automatic conversion of mainstream industrial protocols (such as Modbus and OPC UA); developing lightweight edge gateways to complete data cleansing and format standardization at the device side, thereby reducing platform-layer load.
Traditional construction enterprises rely on hierarchical approval processes, which conflict with the flattened digital management model. Optimization strategies include: promoting organizational change in phases, first implementing the "platform + project team" model in pilot projects to accumulate experience before gradually expanding; constructing a digital capability training system to enhance frontline personnel's technical operations and data literacy through virtual simulation platforms.

Data silos among equipment suppliers, design institutes, and maintenance parties severely restrict full-chain collaboration. Optimization strategies include: jointly building an industrial metaverse collaboration platform to achieve full-chain data sharing for demand forecasting, capacity allocation, and fault tracing based on digital threads; introducing smart contract mechanisms to automatically execute cooperative agreement terms through blockchain, thereby enhancing the transparency and efficiency of upstream and downstream collaboration.

3.3 Key Success Factors

The successful implementation of intelligent systems in communication engineering relies on the deep integration of technology, organization, and ecosystem.

(1) Technological Factors: Openness and Scalability
The system should be equipped with standardized interfaces to support seamless integration of future technological upgrades (such as 6G and quantum communication). For instance, the platform layer should be designed with modular microservices to facilitate the addition of new AI algorithms or hardware drivers.

(2) Organizational Factors: Cultivation of Agile Culture
Break down departmental silos and establish cross-functional agile teams, empowering frontline

personnel with rapid decision-making authority. Utilize digital twin platforms to provide real-time feedback on construction data, forming a management loop of "data-driven - rapid iteration."

(3) Ecosystem Factors: Standardization and Interoperability
Promote the development of unified communication protocols and data exchange standards within the industry to reduce ecosystem collaboration costs. For example, collaborate with industry associations to issue the "Guidelines for Digital Implementation in Communication Engineering," standardizing technology selection and implementation processes.

4. Development Strategies and Trend Outlook

4.1 Three-Dimensional Advancement Strategy

The intelligent transformation of communication engineering necessitates coordinated efforts from three dimensions: technological iteration, management upgrading, and ecosystem construction, forming a strategic closed loop for sustainable development.

(1) Technological Iteration: Forward-Looking Deployment of 6G Intelligent Reconfigurable Surface (RIS)
Taking the opportunity of 6G technology research and development, promote the large-scale application of intelligent reconfigurable surface (RIS) in communication engineering. RIS can dynamically regulate the propagation path of electromagnetic waves to solve the problem of signal coverage blind spots in complex environments. For example, in the deployment of base stations in densely populated urban areas, RIS can replace some traditional physical antennas, reducing construction complexity and energy consumption while supporting the smooth upgrade of future air-ground-space integrated networks. Additionally, it is necessary to simultaneously develop edge intelligent chips and lightweight AI algorithms to enhance the autonomous decision-making capabilities of construction equipment.

(2) Management Upgrading: Blockchain-Enabled Credit Evaluation System
Construct a blockchain-based credit evaluation system for the entire construction process, storing key data (such as contract performance records and quality inspection reports) from design, construction, and acceptance stages on the blockchain. Through smart contracts, automatic triggering of reward and punishment mechanisms can be achieved to incentivize participants to adhere to quality standards. For example, contractors who deliver projects on time and with zero accidents can be awarded blockchain credit points, giving them priority in participating in subsequent project bidding and forming a virtuous competitive ecosystem.

(3) Ecosystem Construction: Industrial Metaverse Collaborative Platform
Integrate digital twin, blockchain, and AR/VR technologies to create an industrial metaverse platform for communication engineering. This platform supports real-time collaboration among designers, contractors, equipment suppliers, and operation and maintenance parties in a virtual space, simulating construction plans, optimizing resource allocation, and accumulating an industry knowledge base. For example, through metaverse simulation, geological risks of optical cable laying paths can be predicted, reducing trial-and-error costs in actual construction and driving the industrial chain to transition from "physical collaboration" to "digital twin collaboration."

4.2 Risk Prevention and Control Mechanism

The intelligent transformation is accompanied by new types of risks, necessitating the construction of a multi-level prevention and control system to ensure engineering safety and data credibility.

(1) Zero Trust Network Security Architecture
Given the characteristics of multi-terminal access in communication engineering, adopt the Zero Trust security model and implement a "continuous verification, least privilege" strategy. Use micro-segmentation technology to divide construction data domains and combine behavioral analysis AI to detect abnormal operations in real time (such as unauthorized device access and abnormal command issuance). For example, when remotely controlling tower crane operations, the system must dynamically verify the operator's identity and command compliance, blocking unauthorized actions.

(2) Federated Learning Data Privacy Protection
To address the risk of privacy leakage in cross-enterprise data sharing, introduce the Federated Learning framework. After training models locally, each participant only uploads encrypted parameters to the platform for aggregation, ensuring that original data does not leave its domain. For example, in a construction quality prediction scenario, multiple enterprises can jointly train an AI model to improve prediction accuracy while preventing the leakage of sensitive data (such as equipment failure records).

4.3 Future Evolution Directions

Communication engineering will evolve deeply towards the directions of "self-adaptation" and "unmanned operation," with the integration of cutting-edge technologies giving rise to entirely new paradigms.

(1) Command Systems Secured by Quantum Communication
Construct highly secure engineering command systems based on Quantum Key Distribution (QKD) technology to achieve absolute eavesdropping prevention and tamper resistance for construction instructions. In highly sensitive scenarios such as defense communications and cross-border submarine optical cables, quantum communication can ensure end-to-end security for critical instructions, circumventing potential vulnerabilities of traditional encryption technologies.

(2) Embodied AI Construction Robot Swarms
Develop embodied AI robot swarms with environmental perception and collaboration capabilities to replace high-risk manual operations. For example, in scenarios involving high-altitude installation of base stations, robots can identify equipment interfaces through multi-modal sensors, autonomously complete bolt tightening and cable connections, and achieve task allocation and obstacle avoidance through swarm intelligence algorithms, thereby increasing construction efficiency by more than three times that of manual operations.

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