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Enhancing Energy-Saving Capability in Metro Construction Within Ecologically Sensitive Areas: A Meta-Network Framework for Innovative Construction Management

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Abstract

Metro construction in ecologically sensitive areas faces a major construction management challenge, as high energy use and environmental impacts can compromise the construction legitimacy required under strict regulations. Existing studies mainly focus on isolated technical solutions or retrospective evaluations, providing limited guidance on their systematic integration into project-level management. This study develops a five-stage meta-network framework grounded in Resource Dependence Theory (RDT) to assess and enhance energy-saving capability by translating external legitimacy pressures into manageable internal resource relationships. The framework systematically evaluates energy-saving capability by analyzing coordination among agents, tasks, energy types, and knowledge. Using Wuxi Metro Line 5 as a case study, clear stage-specific variations are identified, with task–energy matching reaching its lowest level during earth excavation and the recurrence of task–energy resource relationships reaching its highest level during main structure construction. Results show that energy-saving capability can be strengthened through coordinated resource integration, while energy-structure transformation contributes to managing external dependencies and maintaining construction legitimacy. The framework supports proactive construction management by diagnosing coordination deficiencies and guiding resource optimization, while extending RDT to sustainable metro construction management.

Keywords: metro construction; innovative construction management; energy-saving capability; meta-network analysis; resource dependence theory

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1. Introduction

Ecologically sensitive areas are characterized by fragile ecosystems, high levels of biodiversity, and critical ecological functions, making them particularly vulnerable to disturbances from infrastructure construction [1]. To safeguard these areas, infrastructure projects must comply with stringent regulations, such as the EU's Natura 2000 network and national conservation redlines [2,3]. However, continued urbanization and growing demand for urban transport infrastructure have driven metro expansion into or near these areas, intensifying the tension between infrastructure development and ecological protection [4]. Metro construction relies heavily on machinery, material transportation, and temporary facilities, resulting in substantial energy consumption and environmental impacts

[5]. In ecologically sensitive areas, these activities exacerbate issues like soil erosion, water pollution, and habitat disturbance [6,7]. These environmental impacts may increase the risk of regulatory non-compliance and trigger regulatory intervention or public opposition, potentially leading to project delays, increased costs, or construction suspension [8]. Therefore, metro projects in these areas require an integrated construction management approach that coordinates energy use, construction activities, stakeholder responsibilities, and ecological compliance to support project delivery and maintain construction legitimacy [9]. However, technological measures and reactive mitigation alone may be insufficient to achieve these goals. A more proactive approach involves strengthening internal organizational capabilities by coordinating project participants, construction tasks, energy resources, and specialized knowledge to integrate individual energy-saving measures into sustained project-level management practices [10,11]. Such coordination can translate external environmental constraints into internal resource-management decisions, supporting reductions in energy consumption and ecological risks. Thus, enhancing energy-saving capability is not merely a technical objective but also a critical construction management priority for balancing infrastructure development, ecological protection, and project delivery in ecologically sensitive areas [12,13].

To improve energy management in metro construction, prior studies have proposed a range of technological and operational strategies. For example, advanced ventilation control methods, including time delay-compensated gain-scheduled control and period-adaptive proportional–integral–derivative control, have achieved energy savings of 10.33% and 4%, respectively, without reducing indoor air quality [14,15]. Other studies have applied multi-objective optimization to balance air quality, energy consumption, and system stability [16]. At the equipment level, coordinated operation of energy storage and regenerative energy devices, optimized using algorithms such as the non-dominated sorting genetic algorithm, has improved efficiency by up to 36.72% [17]. In addition, coupled simulation models for components such as capillary heat exchangers have been used to improve waste heat recovery [18]. Although these studies provide important technical advances and innovative solutions, most focus on isolated equipment or subsystem performance. As a result, they offer limited insight into how project organizations coordinate, adapt, and integrate these measures within construction management processes under changing ecological and regulatory conditions. To convert individual solutions into a stable project-level energy-saving capability, particularly in ecologically sensitive areas, an integrated framework that supports both systematic assessment and management coordination is needed. This framework should evaluate not only technical performance but also how these strategies can be effectively implemented through project-level coordination and resource integration to reduce energy use, lower ecological compliance risk, and maintain the construction legitimacy required for project advancement [19].

Existing studies on energy-saving assessment generally adopt four approaches: macro-statistical evaluation, technical modeling and simulation, data-driven prediction, and multi-criteria decision analysis. Macro-statistical methods, such as difference-in-differences and panel regression, use large datasets to estimate the effects of energy policies at regional or national levels [20]. Technical assessment methods, including building energy simulation and life cycle assessment, are used to evaluate energy performance and environmental impacts [21,22]. Data-driven approaches, using IoT monitoring and machine learning, support timely energy performance evaluation and prediction [23]. Multi-criteria decision-making methods, such as the analytic hierarchy process, provide structured assessments at the enterprise or project level by integrating multiple performance indicators. Although valuable, these approaches primarily focus on policy effects, technical performance, or aggregated evaluation results, providing limited insight into organizational resource coordination during metro construction in ecologically sensitive areas

[24]. In particular, they may not adequately capture how stakeholder interactions and resource dependencies vary across construction stages under ecological and regulatory constraints [25]. Furthermore, existing methods offer limited explanations of how energy-saving capability develops through organizational coordination and resource allocation, or how such capability supports the management of external dependencies and construction legitimacy [26]. Meta-network analysis offers a complementary approach by representing heterogeneous entities and their relationships within an integrated network, enabling quantitative analysis of complex interactions [27]. By modeling agents, tasks, energy resources, and knowledge across construction stages, this approach can reveal structural patterns of resource coordination and identify potential management weaknesses. These insights can inform targeted resource allocation and coordination strategies to support energy-saving management under ecological constraints [28]. However, existing meta-network applications require further adaptation to the specific ecological constraints and stage-dependent resource relationships of metro construction projects in sensitive areas.

To address this gap, this study develops a meta-network framework grounded in Resource Dependence Theory (RDT) to assess and support improvements in the energy-saving capability of metro construction projects in ecologically sensitive areas. The framework conceptualizes energy-saving capability as a project-level organizational capability shaped by the coordinated configuration of project participants, tasks, knowledge, and energy types, rather than as an inherent project attribute. It evaluates energy-saving capability through indicators of energy structure, task–energy matching, agent–energy control compatibility, and task–knowledge coordination, thereby revealing stage-specific patterns of energy-related resource coordination. From an RDT perspective, this study examines how external ecological and regulatory requirements are reflected in internal task assignments, energy resource control, and knowledge support, extending RDT to energy-saving management in metro construction. Unlike conventional assessments that focus mainly on total energy consumption, the proposed framework diagnoses how energy-related resources are organized and coordinated under ecological and regulatory constraints. In practice, it helps project managers identify weaknesses in resource configuration and opportunities to improve organizational coordination and energy-saving management. By linking external legitimacy requirements with internal resource coordination, the framework provides a basis for shifting from reactive compliance toward proactive energy-saving construction management in ecologically sensitive areas.

2. Literature Review

2.1. Resource Dependence Theory

Resource dependence theory provides a useful framework for understanding how organizations manage external dependencies to maintain performance and continuity. It assumes that no organization is fully self-sufficient; instead, organizations must interact with their external environment to obtain critical resources [29]. From this perspective, organizations operate as open systems embedded in networks of interdependence shaped by resource availability, environmental uncertainty, and strategic adaptation [30]. Because dependence on external resources can create power imbalances, organizations often take strategic actions to reduce vulnerability and improve control [31]. These actions may include reconfiguring internal structures, adjusting governance arrangements, and forming partnerships to stabilize resource flows and limit external influence [32]. Such reconfiguration helps organizations reduce uncertainty while strengthening legitimacy and strategic control [33]. In metro construction projects located in ecologically sensitive areas, strict regulatory requirements and public scrutiny increase dependence on external approval, making construction legitimacy a critical resource [34]. Drawing on RDT, this study treats energy-saving capability as a strategic means of managing this dependency. The pressure

to secure construction legitimacy arises from the need to reduce the high energy intensity of construction activities and the ecological disturbances they may cause in vulnerable environments. In response, metro construction project organizations must integrate internal resources to build energy-saving capability and demonstrate energy conservation performance as evidence of responsible construction practice.

2.2. Energy-Saving Capability and Its Measurement in Ecologically Sensitive Metro Construction Projects

Energy-saving capability is a comprehensive indicator of how effectively a system or organization uses energy and how much potential it has to reduce energy consumption while performing its required functions [35]. In metro construction, this capability is especially important because projects typically involve high energy use, long construction periods, underground operations, and coordination across multiple trades [36]. These features make energy-saving capability a system-level issue shaped by changing conditions and multiple interacting factors. As a result, effective energy management in metro construction depends not only on reducing total consumption, but also on optimizing energy structure and controlling energy use across the full construction process [37,38]. In metro projects located in ecologically sensitive areas, energy-saving capability can be defined as a strategically integrated organizational capacity developed to manage dependence on critical external resources while achieving whole-process energy conservation [39]. In this context, the capability is not limited to technical energy efficiency. It also includes the project's ability to maintain and strengthen construction legitimacy through proactive ecological coordination and long-term benefit management, thereby supporting smooth implementation and sustainable operation in sensitive environments [40]. Existing studies have mainly examined energy-saving capability through three perspectives: energy consumption monitoring and management, application of energy-efficient construction technologies, and resource recycling efficiency [41]. Energy monitoring and management focus on real-time collection, analysis, and optimization of energy use data during construction, often through digital or information-based tools [42]. Research on energy-efficient construction technologies emphasizes low-energy and low-emission processes, equipment, and materials. Resource recycling efficiency focuses on waste reuse and cascading energy utilization [43]. Although these perspectives provide useful insights, they do not fully address the organizational and ecological coordination demands of metro construction in ecologically sensitive areas. Because these projects operate under limited environmental carrying capacity and strict regulatory requirements, they require an assessment framework that can systematically diagnose and improve internal resource management practices [44]. From the perspective of RDT, project organizations can internalize external constraints into their operations by structuring and governing internal energy use. Accordingly, energy-saving capability is defined in this study as a set of observable internal relationships that capture how energy use is coordinated, controlled, and supported within the project system [45]. Based on this logic, the proposed indicators are developed to reflect three key aspects: process and structural optimization, clarification of control responsibilities, and knowledge-based diagnostic support. Process and structural optimization evaluates the allocation and flow efficiency of energy across project tasks. Clarification of control responsibilities identifies the actual authority and accountability of different management actors in relation to energy use. Knowledge-based diagnostic support examines gaps between the existing knowledge base and the specific requirements of project tasks. Together, these aspects provide a practical basis for assessing and strengthening energy-saving capability in ecologically sensitive metro construction projects.

2.3. Metro Construction Stages and Stage Specific Energy Assessment

Metro construction is a staged process, and its energy assessment should therefore be conducted on a stage-specific basis rather than through a single project-level evaluation. The construction process can be divided into five stages: pipeline relocation and traffic diversion, retaining structure construction, earth excavation, main structure construction, and traffic restoration [46,47]. Because each stage differs in work tasks, resource inputs, and environmental interactions, it also presents distinct patterns of energy consumption and ecological risk [48]. Accordingly, energy assessment should be aligned with the dominant characteristics of each stage. In the pipeline relocation and traffic diversion stage, energy consumption is relatively low, but the process involves substantial interaction with local communities. Therefore, energy assessment at this stage should focus on strategic compliance, particularly how energy-related decisions mitigate social risks and support project legitimacy [49]. In the retaining structure construction stage, construction activities begin to intensify, involving increased use of machinery and materials [50]. Energy assessment at this stage should emphasize the coordination of energy use and resource allocation across tasks to ensure efficient and stable energy supply [51]. The earth excavation stage is characterized by intensive use of heavy machinery and high fuel consumption; assessment at this stage should emphasize process efficiency, such as task-level energy use intensity [52]. High energy intensity during excavation may also increase local air pollution and noise, which are critical concerns in ecologically sensitive areas [53]. The main structure construction stage requires complex coordination among multiple participants and technologies. Accordingly, energy assessment at this stage should focus on structural integration, including the effectiveness of knowledge sharing and resource allocation [54]. In the traffic restoration stage, construction activities gradually decrease, and the focus shifts to system recovery and environmental restoration [55]. Energy assessment at this stage should emphasize energy efficiency in final operations and the consolidation of energy-saving practices to support long-term sustainability. By matching assessment priorities to the characteristics of each construction stage, project managers can identify stage-specific bottlenecks, allocate resources more effectively [56], and strengthen energy-saving capability across the project construction [57], thereby improving ecological compliance and reinforcing construction legitimacy.

2.4. The Meta-Network Approach for Energy-Saving Capability Assessment

A meta-network is a modeling and assessment method used to describe and analyze multiple types of entities and their relationships in complex systems [58]. It represents a system as an integrated network with multiple node types and multiple link types, which helps reveal the overall structure of the system and its underlying dynamics [59]. The core elements of a meta-network include node categories, link relationships, and network matrices [60]. Recent studies of construction project stakeholder networks have also emphasized the importance of systematically collected relational data for characterizing project interactions and supporting network-based analysis [61]. Based on matrix operations, the method supports a range of structural and performance metrics, such as network density, centrality, task–resource matching, resource omega, and agent resource fit [62]. The theoretical premise of meta-network analysis is that organizational capability in complex systems depends not only on the attributes of individual elements but also on their relational structures and resource coordination [63]. For project systems involving interdependencies among multiple agents, tasks, and resources, the relationships among these elements reflect the structural conditions for resource allocation, task execution, and organizational coordination. Accordingly, examining network relationships and their degree of alignment can help identify potential resource dependencies, allocation gaps, and coordination deficiencies. Importantly, network structures reflect the structural conditions for

organizational coordination rather than directly measured resource-use efficiency or actual performance outcomes. In metro construction projects in ecologically sensitive areas, stringent ecological protection requirements and external regulatory pressures require project organizations to coordinate project participants, energy-saving tasks, energy resources, and specialized knowledge during construction to meet project implementation and environmental compliance requirements [64]. This aligns with the meta-network approach to representing multiple entity types and their relationships within an integrated framework [65]. Through its link structure, the meta-network method can represent how different project actors control, access, and depend on key resources such as energy and knowledge [66]. Furthermore, stage-specific network matrices and corresponding indicators can reveal variations in resource relationships and potential coordination deficiencies, providing a basis for management interventions and resource optimization [67].

Based on the above theoretical analysis, this study examines organizational energy-saving capability in metro construction projects in ecologically sensitive areas from two perspectives: task–energy resource matching and agents' resource control and knowledge support. First, as discussed in Section 2.3, construction tasks and resource requirements change as metro construction progresses through different stages. Accordingly, the relationships between tasks and energy resources, as well as their degree of alignment, may also vary. Such stage-specific differences can be identified through changes in task–energy relationships and corresponding structural indicators within the meta-network. Therefore, the following research proposition is formulated:

Proposition 1 (P1). *Differences in construction tasks and energy-resource requirements across project stages are expected to be reflected in distinct patterns of task–energy matching and energy-resource relationships within the project meta-network.*

Second, from an organizational network perspective, project agents differ in their responsibilities, resource-control relationships, and knowledge support. During metro construction, different agents undertake different tasks and have varying resource requirements. When agents' control over energy resources or knowledge support does not align with task requirements, resource-alignment gaps and knowledge-demand deviations may arise. By analyzing the relationships among agents, tasks, energy resources, and knowledge, the meta-network approach can identify these potential structural differences. Based on this reasoning, the following research proposition is formulated:

Proposition 2 (P2). *Differences in project agents' responsibilities, energy-control relationships, and knowledge support are expected to be reflected in variations in agent–energy control compatibility and task–knowledge demand deviation.*

These propositions aim to examine stage-specific and agent-specific differences in organizational energy-saving capability from a network-structural perspective, rather than to directly test the causal effects of resource coordination on actual energy consumption or construction legitimacy. The subsequent analysis examines these propositions through the A–T–E–K meta-network framework, using corresponding structural indicators and evidence from the case study.

3. Research Framework

Based on Resource Dependence Theory (RDT), this study applies Meta-Network Analysis (MNA) to develop a framework for assessing and enhancing the energy-saving capability of metro construction projects in ecologically sensitive areas, as illustrated in Figure 1. The framework captures the interdependencies among construction agents,

tasks, energy types, and energy-related knowledge. First, a meta-network model is constructed to represent relationships among these entities. Data from the academic literature, construction documents, expert interviews, and questionnaire surveys are used to identify four node types—Agents (A), Tasks (T), Energy (E), and Knowledge (K)—and five relationship types: AT, AE, AK, ET, and TK. Corresponding meta-matrices are then constructed to represent these relationships across the five construction stages. Second, energy-saving capability is assessed using the constructed meta-network and the ORA measurement approach. Four evaluation indicators are calculated: Task–Energy Demand Matching Degree (TE), Energy Omega (EO), Agent–Energy Control Compatibility (AE_i), and Task–Knowledge Demand Deviation (TK_i). Using the meta-matrix data, these indicators characterize organizational energy-saving capability across the five construction stages, enabling the identification of stage-specific weaknesses in resource coordination and areas for management improvement.

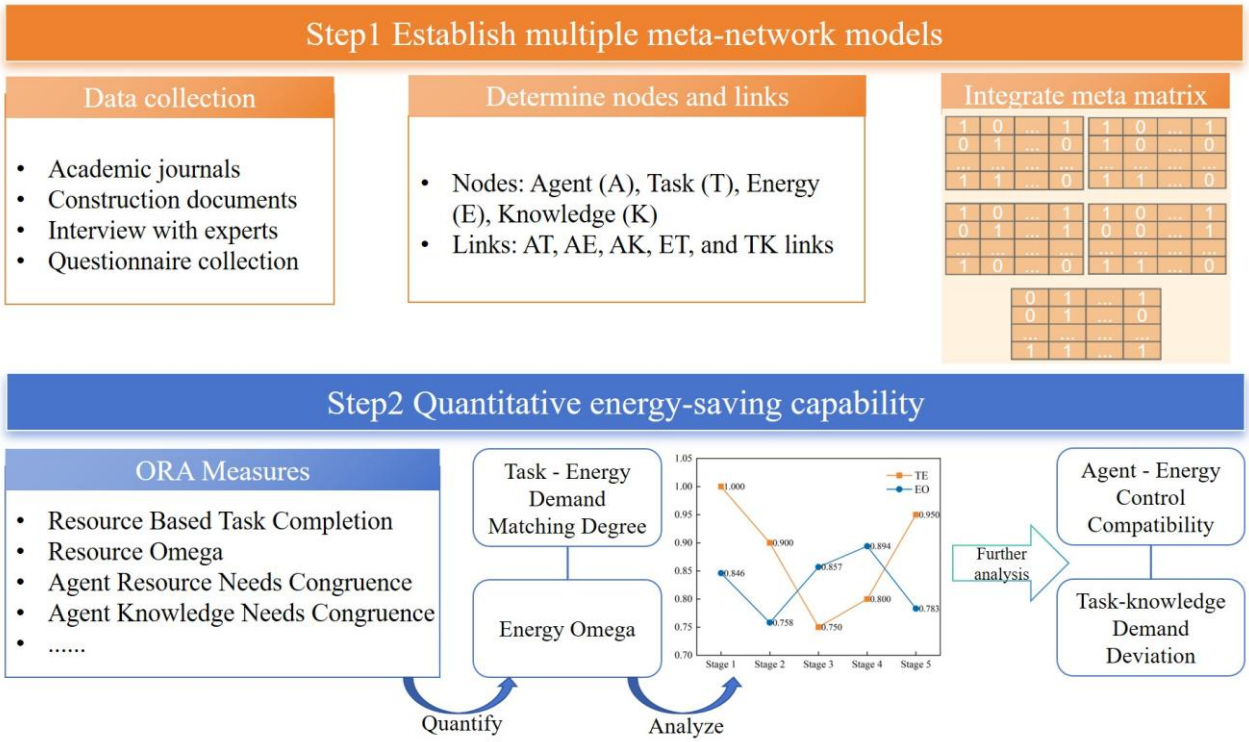


Figure 1. Research framework.

3.1. Establish Multiple Meta-Network Models

In a meta-network, different node types represent distinct elements within a system, and their classification should align with the system's core characteristics [68]. Metro construction projects in ecologically sensitive areas must comply with stringent ecological regulations while pursuing energy conservation. Assessing and enhancing energy-saving capability in this context requires examining how external legitimacy pressures are reflected in internal resource coordination. Based on the theoretical premise outlined in Section 2.4, organizational energy-saving capability depends not only on energy resources themselves but also on task assignments, agents' control over energy resources, and specialized knowledge supporting task implementation. Accordingly, this study classifies these elements into four node types, Agents (A), Tasks (T), Energy (E), and Knowledge (K), to represent the resource dependencies and coordination relationships underlying energy-saving management within the project under ecological constraints [69–72]. Specifically, Agents represent the stakeholders involved in the project, Tasks include the

energy-saving measures implemented during construction, Energy includes energy sources (e.g., electricity and diesel) and energy-related resources (e.g., water), whose management may involve energy-consuming processes such as pumping and recycling, and Knowledge encompasses the energy-saving technologies and skills applied throughout the project. The detailed definitions and coding of the A–T–E–K nodes are provided in Table A1. Based on the metro construction process, the energy-saving capability assessment network can be developed separately for each of the five stages: pipeline relocation and traffic diversion, retaining structure construction, earth excavation, main structure construction, and traffic restoration.

The connections between nodes represent resource dependencies and coordination relationships among project elements. In metro construction projects in ecologically sensitive areas, the A–T–E–K meta-network provides a structural representation of internal resource coordination under external legitimacy pressures. In the subsequent calculations, ordinary arithmetic matrix multiplication is applied to the binary relational matrices rather than Boolean matrix multiplication. The resulting values represent the number of indirect relational paths between nodes, where zero indicates no path and a positive value indicates at least one path. Each relational sub-network is represented by a binary adjacency matrix. For each construction stage, five meta-matrices, [AT], [AE], [AK], [ET], and [TK], are constructed to represent relationships among the A–T–E–K node types. A value of 1 indicates the presence of a link between two nodes, whereas 0 indicates its absence. To ensure consistent matrix operations, the row and column orientations are defined as follows. Let n_a, n_t, n_e, and n_k denote the numbers of agents, tasks, energy, and knowledge nodes, respectively, at each construction stage. The matrices are defined as [AT] ($n_t \times n_a$), [AE] ($n_a \times n_e$), [AK] ($n_a \times n_k$), [ET] ($n_t \times n_e$), and [TK] ($n_t \times n_k$). Matrix labels indicate relationship types rather than necessarily the order of row and column node sets. These orientations are applied consistently across all five construction stages, and the meanings of these relationships are illustrated in Figure 2. After identifying the nodes and their relationships, the corresponding meta-matrices are compiled and imported into Organizational Risk Analyzer (ORA) [73]. ORA is then used to construct the stage-specific meta-networks, compute group-level indicators, and compare resource coordination structures across construction stages to provide a data basis for the subsequent analysis of the research propositions.

3.2. Quantifying the Energy-Saving Capability

After developing the five-stage energy-saving capability assessment networks, it is essential to select appropriate evaluation indicators to quantify these networks. In this study, energy-saving capability refers to the organizational and network-level capacity to coordinate agents, tasks, energy resources, and knowledge in support of energy-saving measures, rather than directly measured energy consumption or savings. Unlike traditional network measures such as density and centrality, Carley [74] proposed indicators including resource-based task completion, resource omega, agent resource needs congruence, and agent knowledge needs congruence to capture various aspects of resource allocation, utilization, control, and the knowledge underlying resource use. Building on this foundation and guided by RDT, this study adapts these indicators to the context of metro construction in ecologically sensitive areas, resulting in four tailored metrics: Task–Energy Demand Matching Degree (TE), Energy Omega (EO), Agent–Energy Control Compatibility (AE_i), and Task–Knowledge Demand Deviation (TK_i). Specifically, TE and EO are used to examine the stage-specific differences in task–energy matching and energy-resource relationship structures addressed in Proposition 1 (P1), while AE_i and TK_i are used to examine how differences in agents' responsibilities, energy-control relationships, and knowledge support are reflected in energy-control compatibility and task–knowledge

demand deviation, as proposed in Proposition 2 (P2). The definitions and calculation methods of the above four indicators are presented as follows.

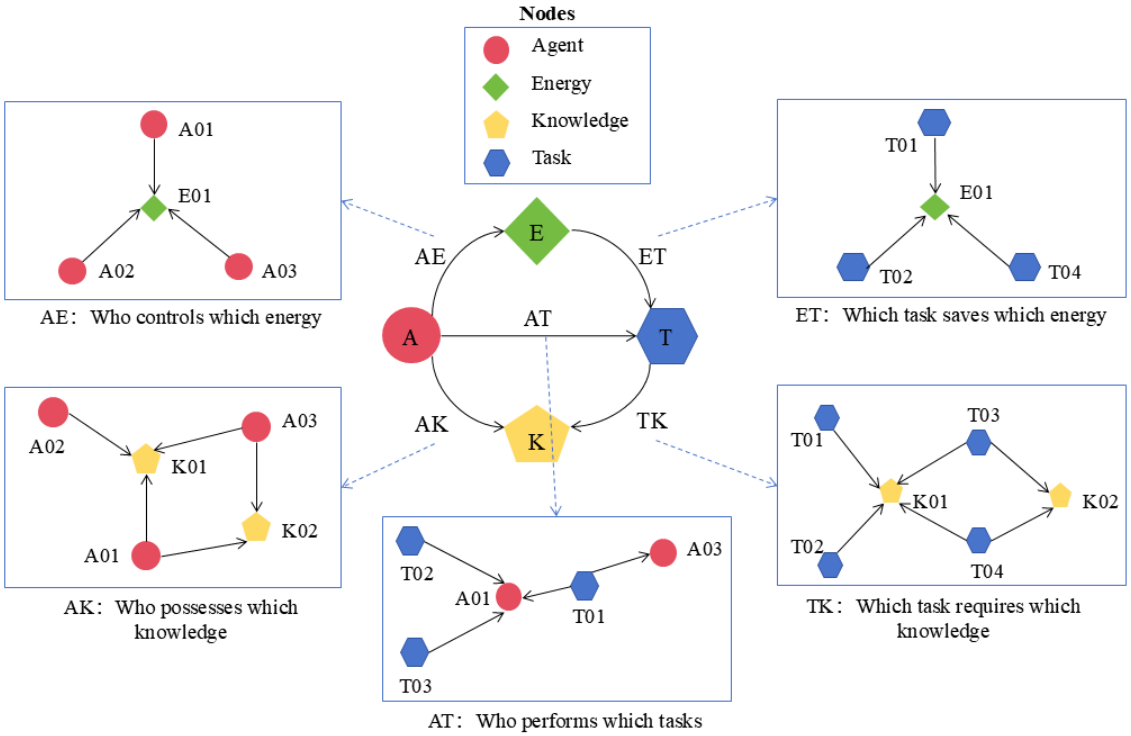


Figure 2. "A–T–E–K" meta-network conceptual model.

3.2.1. Task–Energy Demand Matching Degree

In metro construction projects located in ecologically sensitive areas, maintaining construction legitimacy requires mitigating the ecological impacts associated with energy use [75]. Meeting relevant environmental requirements depends partly on the project organization's ability to coordinate energy use during construction [76]. In this context, the alignment between energy-saving tasks and the energy types used to perform them becomes a critical internal mechanism. The TE indicator captures this mechanism by assessing the structural alignment among task–energy relationships, task assignments, and agents' energy-control relationships. A high TE value indicates a higher degree of structural alignment between task-related energy requirements and the energy resources represented in the network. Such alignment may support more effective energy management, but it does not directly demonstrate a reduction in actual energy consumption or ecological disturbance. In this way, the indicator converts external legitimacy pressure into a measurable internal variable: the organization's ability to optimize task–energy matching. This matching process requires agents to organize and implement energy-saving tasks, exercise control over energy use, and consider the impacts of task execution on energy consumption. Therefore, the binary matrices AT (task × agent), AE (agent × energy), and ET (task × energy) are used as inputs. The calculations are expressed as follows:

$$S_E = AT \cdot AE \tag{1}$$

$$R_E = ET \tag{2}$$

$$I = \{t | \exists r,\ R_E(t,r) = 1 \wedge S_E(t,r) = 0\} \tag{3}$$

$$TE = (|T| - |I|)/|T| \tag{4}$$

where AT denotes the AT matrix, AE denotes the AE matrix, ET denotes the ET matrix, S_E denotes the energy resources that can be effectively supplied through the integration of task assignments and agent–energy control, R_E denotes the energy requirements of tasks, t denotes a specific task, r denotes a specific energy type, I denotes the subset of tasks that fail to achieve effective task–energy matching, $|I|$ denotes the number of mismatched tasks, and $|T|$ denotes the total number of tasks.

3.2.2. Energy Omega

In metro construction projects in ecologically sensitive areas, maintaining construction legitimacy requires organizations to coordinate energy resources under ecological constraints [77]. Different energy types have different environmental impacts; for example, diesel-powered equipment produces direct exhaust emissions, whereas electric equipment generates no on-site exhaust during operation [78]. Therefore, energy-saving management should consider these environmental differences [79], while network-based analysis can examine how energy types are associated with construction tasks. The EO indicator characterizes these relationships by measuring the extent to which the same energy type is associated with multiple construction tasks. A higher EO value indicates more repeated task–energy associations, reflecting structural patterns of energy-resource dependence rather than actual reductions in energy consumption or improvements in energy efficiency. Because EO is calculated from binary task–energy relationships, it does not account for energy consumption quantities or differences in environmental impacts among energy types. Importantly, repeated associations indicate that an energy type is linked to multiple tasks, not that energy is physically reused, recovered, or transferred between tasks. Thus, EO provides a structural measure of energy-resource dependencies that project organizations must coordinate under external ecological constraints. The EO indicator is calculated using the task–energy (ET) matrix as follows:

$$\text{Count}(e) = \sum_{t} E\,T(t,e) \forall e \tag{5}$$

$$EO = \frac{\sum_{e} \max(0, \text{Count}(e) - 1)}{\sum_{t} \sum_{e} E\,T(t,e)} \tag{6}$$

where ET denotes the matrix formed by the ET network, $ET(t,e)$ indicates whether task t involves energy type $\text{Count}(e)$ denotes the number of tasks associated with energy type e, e denotes a specific energy type, t denotes a specific task, $\sum_{e} \max(0, \text{Count}(e) - 1)$ represents the total number of repeated task–energy associations beyond the first association for each energy type, and $\sum_{t} \sum_{e} E\,T(t,e)$ denotes the total number of task–energy relationships. Thus, EO is determined solely by the structure of the ET matrix and does not account for differences in energy consumption or environmental impact among energy types. As E also includes energy-related resources, EO reflects repeated task–resource associations rather than relationships among energy sources alone.

3.2.3. Agent–Energy Control Compatibility

In metro construction projects in ecologically sensitive areas, construction legitimacy relies on both overall energy performance and the effectiveness of individual participants in completing their energy-saving tasks [80]. Different actors, such as equipment operators, site managers, and subcontractors, have different levels of control over energy use [81]. Weaknesses at the participant level can therefore reduce the effectiveness of the project's overall energy-saving capability [82]. The AE_i indicator captures this aspect by measuring the structural compatibility between the energy resources required by an agent's assigned tasks and the energy-control relationships represented in the network. Following

the logic that resource mismatches may reveal capability gaps, a low AE_i value indicates insufficient alignment between task-related energy requirements and the agent's energy-control relationships. Such structural mismatches may indicate potential coordination weaknesses relevant to ecological compliance and construction legitimacy, but they do not directly demonstrate ineffective energy control or actual energy-saving outcomes. Thus, this indicator translates the external demand for reliable energy performance into a measurable internal variable: participant-level control gaps that can be identified and addressed to strengthen the project's overall capacity to manage legitimacy dependence. This evaluation requires clarifying task assignments, specifying the energy resources required for task execution, and ensuring that control responsibilities over these resources are properly aligned with agents. Therefore, the matrix values formed by inputting the three sub-networks of AT, AE, and ET are calculated as follows:

$$NE = AT^{'} \cdot ET \tag{7}$$

$$AE_i = \frac{\sum[NE(i,:) .* AE(i,:)]}{\sum[NE(i,:)]} \tag{8}$$

where $AT^{'}$ denotes the transpose of the task–agent relationship matrix AT, ET denotes the task–energy relationship matrix, $NE(i,:)$ denotes the energy control requirements of agent i inferred from assigned tasks, and $AE(i,:)$ denotes the actual energy control vector of agent i. In Equation (7), "·" denotes ordinary matrix multiplication, whereas "*" in Equation (8) denotes element-wise multiplication of the corresponding row vectors, and Σ represents the summation of their elements. Accordingly, AE_i measures the proportion of task-related energy-demand paths covered by the corresponding energy-control relationships of agent i. A higher AE_i value indicates greater structural compatibility between the agent's energy requirements and energy-control relationships.

3.2.4. Task–Knowledge Demand Deviation

In the context of metro construction in ecologically sensitive areas, securing construction legitimacy requires the effective implementation of energy-saving measures, which in turn depends on adequate technical and operational knowledge [83]. This includes understanding efficient equipment use, applying appropriate measures at the right time, and adapting to changing site conditions [84]. Because participants may differ in their relevant knowledge, mismatches between task requirements and available expertise can reduce execution quality [85]. The TK_i indicator captures this aspect by measuring the extent to which the knowledge required for a given task exceeds the knowledge possessed by the agents responsible for carrying it out. A higher TK_i value indicates a larger structural gap between task-related knowledge requirements and the knowledge resources associated with the responsible agents. This may suggest a need for additional training, knowledge transfer, or technical coordination. However, the indicator does not directly measure individual technical proficiency or the actual energy-saving outcomes of task implementation. Accordingly, TK_i provides a structural measure of potential knowledge-support gaps in task implementation under ecological and regulatory constraints. This evaluation requires identifying the tasks assigned to agents, clarifying the knowledge possessed by agents, and ensuring that task implementation is adequately supported by the corresponding knowledge. Therefore, the sub-networks AT, AK, and TK are used as inputs, and the calculation formula is as follows:

$$NK = AT' \cdot TK \tag{9}$$

$$TK_i = \frac{\sum[NK(i,:).*\sim AK(i,:)]}{\sum[NK(i,:)]} \tag{10}$$

where AT' denotes the transpose of the AT matrix, TK denotes the TK matrix $NK(i,:)$ denotes the knowledge requirement vector of agent i derived from assigned tasks, $AK(i,:)$ denotes the actual knowledge vector possessed by agent i, $\sim AK(i,:)$ denotes the knowledge that agent i does not possess.

4. Case Study

To illustrate the application of the proposed five-stage framework for assessing and enhancing energy-saving capability, this study examines a large-scale rail transit project located in an ecologically sensitive area. This case provides a suitable empirical setting because stringent ecological constraints impose external legitimacy pressures, while the coexistence of electric and conventional fuel-powered equipment provides a practical context for examining internal resource coordination. In addition, the available project data provide a basis for constructing the A–T–E–K meta-network and comparing resource coordination structures across the five construction stages.

4.1. Case Introduction

This study applies the proposed Resource Dependence Theory (RDT)-based meta-network framework to Tangcheng Station of Wuxi Metro Line 5 to assess energy-saving capability under ecological constraints. The project is located in a national public welfare forest area in Binhu District, Wuxi, near protected scenic areas and within an area covered by national environmental monitoring stations. These ecological and regulatory conditions impose substantial external legitimacy pressures, requiring the project to comply with stringent environmental standards. In practice, these requirements involve strict controls on dust, noise, and other construction-related environmental impacts, alongside efforts to limit the use of high-emission fuel-powered equipment through targeted electrification. In response, the project adopted an electrification-oriented construction approach, introducing electric equipment for suitable activities while retaining conventional fuel-powered equipment where technical or operational constraints limited electrification. Rather than eliminating fossil fuel use entirely, the project prioritized the replacement of energy-intensive and high-emission machinery where feasible, aiming to optimize its energy structure and reduce energy consumption, carbon emissions, and local environmental disturbances. This approach provides a practical setting for examining how project stakeholders coordinate energy resources, construction tasks, and responsibilities under ecological constraints. To capture stage-specific differences in resource coordination and energy-saving capability, the project is divided into five construction stages, as shown in Figure 3.

4.2. Data Collection and Meta-Network Modeling

4.2.1. Overall Framework for Meta-Network Construction

Constructing the A-T-E-K meta-network for metro construction sites in ecologically sensitive areas requires detailed project data, together with the identification of reliable nodes and their interrelationships. The overall modeling process is illustrated in Figure 4.

First, project nodes were preliminarily identified through a literature review of relevant studies, standards, and engineering cases. Based on this review, node elements related to external legitimacy pressure were identified, including participating agents, energy-saving tasks, energy types, and relevant professional knowledge.

Next, expert interviews were conducted to refine the node inventory within the framework of Resource Dependence Theory (RDT) and to distinguish the tasks applicable to each of the five construction stages. The final node inventory is presented in Table A1.

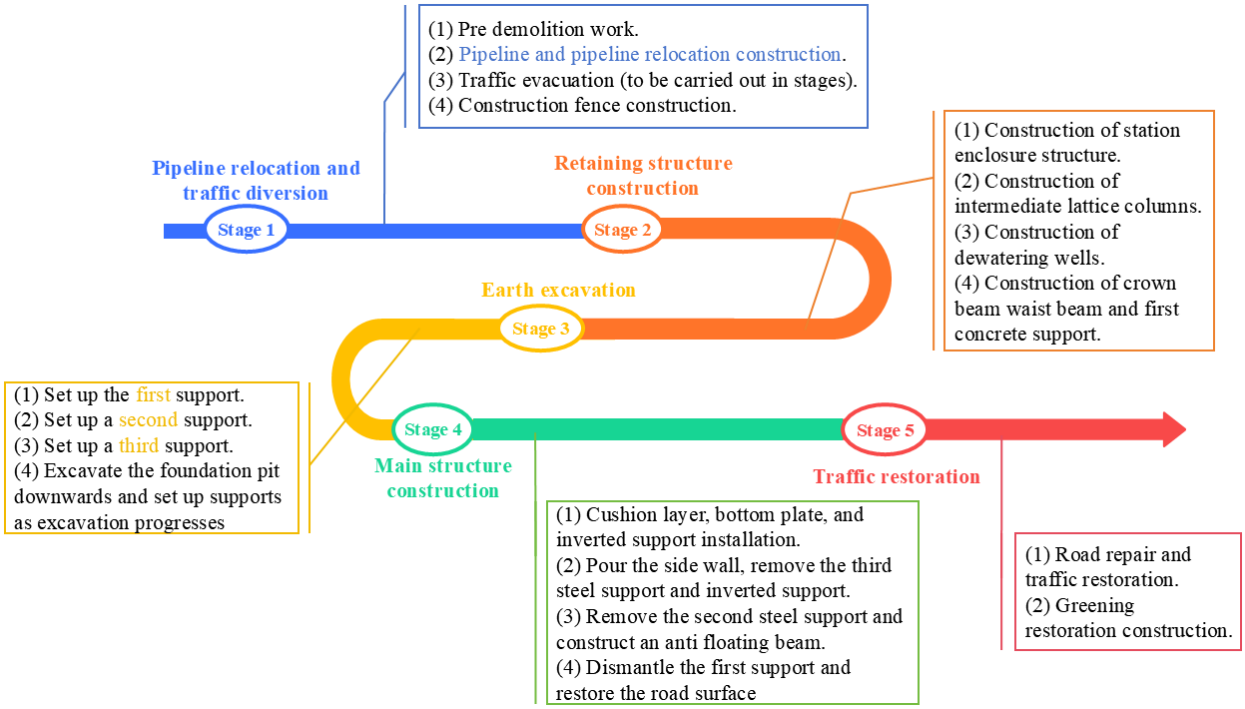


Figure 3. Five-stage construction process of metro projects in ecologically sensitive areas.

A questionnaire was then designed to identify five types of relationships: AT, AE, AK, ET, and TK. These relationships represent how external legitimacy pressures are reflected in internal resource dependencies and coordination arrangements.

Based on the five-stage construction process, the relevant nodes and relationships were organized into stage-specific datasets and converted into five sets of AT, AE, AK, ET, and TK meta-matrices in accordance with the framework presented in Section 3.

Finally, all meta-matrices were imported into the ORA software to visualize the energy-saving conditions across the five construction stages. Matrix-based indicators were then calculated to assess organizational energy-saving capability and identify potential coordination weaknesses.

4.2.2. Data Collection, Questionnaire Design, and Relationship Verification

To operationalize the proposed framework, initial interview materials were prepared based on the relevant literature, construction standards, and site documentation. Following a purposive sampling approach, professionals with relevant experience were selected for face-to-face interviews based on their professional responsibilities and practical experience in metro construction and project management [86]. Specifically, three professionals were interviewed, including one representative from a government regulatory authority and two managers from construction management organizations. Their feedback was used to refine the initial node inventory, identify preliminary relationships among network nodes, and divide the construction process into five stages. Subsequently, a structured questionnaire was developed to collect three types of data: respondents' background information, the energy-saving tasks adopted in each of the five construction stages, and assessments of five network relationship types: Agent–Task (AT), Agent–Energy (AE), Agent–Knowledge (AK), Energy–Task (ET), and Task–Knowledge (TK).

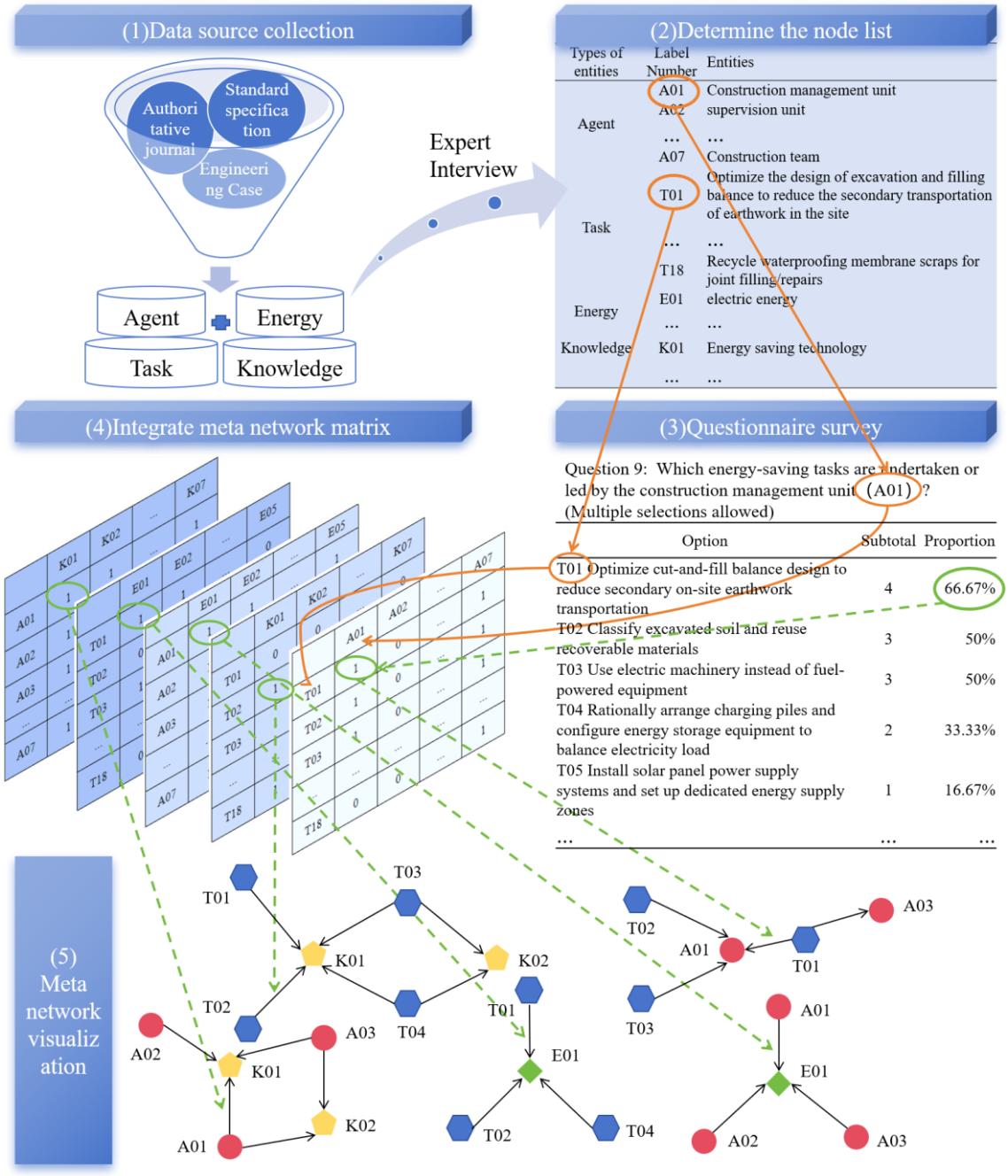


Figure 4. Example of data collection and meta-network modeling.

Following the recommendations of the three initial interviewees, the questionnaire survey was conducted among professionals involved in on-site metro construction activities. Six professionals involved in the Wuxi Metro Line 5 Tangcheng Station project were contacted. Due to the participants' work schedules and difficulties in coordinating interview times, one participant completed the questionnaire through an individual online interview, while the remaining five completed the same questionnaire through Wenjuanxing (an online questionnaire platform). The online interview participant was a representative of the construction management organization, while the other five participants included two from supervision organizations, two from construction teams, and one from a design organization. After questionnaire completion, communication with respondents was maintained through WeChat to obtain feedback on the clarity of questionnaire items and to clarify and verify ambiguous responses when necessary, thereby improving the quality of the collected relational judgment data. All six sets of relational judgments were

considered valid and included in the subsequent analysis. The characteristics of all nine participants are summarized in Table 1.

Table 1. Characteristics of Interviewees and Questionnaire Respondents.

ID	Data Collection Method	Affiliation	Gender	Work Experience
E1	In-person expert interview	Government regulatory authority	Male	6–10 years
E2		Construction management organization (management level)	Male	6–10 years
E3		Construction management organization (management level)	Male	6–10 years
P1	Online expert interview	Construction management organization	Male	Less than 5 years
R1	Online questionnaire	Supervision organization	Male	6–10 years
R2		Construction team	Male	6–10 years
R3		Design organization	Female	6–10 years
R4		Supervision organization	Male	11–15 years
R5		Construction team	Male	6–10 years

The questionnaire employed multiple-choice questions to collect data on five types of network relationships: agents' participation in tasks (AT), agents' control over energy-related resources (AE), agents' knowledge responsibilities (AK), the potential contribution of tasks to energy conservation or utilization (ET), and the knowledge required for task implementation (TK). Taking the AT relationship as an example, respondents were asked, "Which tasks is A01 responsible for performing?" and could select the relevant tasks from 18 options (T01–T18). The multiple-choice responses were coded as binary relational data, with selected options assigned a value of 1 and unselected options assigned a value of 0. These binary values indicate the presence or absence of relationships rather than their strength. To reduce the influence of individual respondents' subjective judgments on relationship identification, relationships selected by at least three of the six respondents (≥50%) were retained as preliminary candidates. This threshold served only as a screening criterion and did not indicate relationship strength or expert consensus. Subsequently, following the principle of data triangulation [87], the research team and respondent P1, a representative of the construction management organization, jointly verified the candidate relationships against the project's construction organization design and site documentation. When candidate relationships identified through questionnaire screening were inconsistent with project documentation, P1 examined the disputed relationships based on actual task assignments and resource allocation arrangements at the corresponding construction stage. The research team and P1 then jointly discussed the relevant evidence and confirmed the final assignments. The final decisions were primarily based on project documentation and verified on-site conditions. Relationships supported by project evidence and confirmed through further verification were retained, whereas those inconsistent with actual stage-specific conditions and not substantiated during verification were excluded. The corresponding meta-network relational matrices were subsequently constructed based on these assignments. Inter-rater agreement across 426 relationship items was evaluated using observed agreement and Fleiss' kappa. As shown in Table 2, the overall observed agreement was 60.02%, with a Fleiss' kappa of 0.187. Across the five relationship types, observed agreement ranged from 49.21% to 69.58%, and Fleiss' kappa ranged from −0.080 to 0.132, indicating limited inter-rater agreement. This variation may reflect differences in respondents' professional roles and interpretations of specific relationships. Accordingly, the final network relationships should be interpreted as project-

specific judgments informed by survey responses, project documentation, and expert discussions, rather than as evidence of strong inter-rater consensus.

Table 2. Inter-rater Agreement for the Five Relational Networks.

Network	Number of Relationships	Observed Agreement (%)	Fleiss′ κ
AT	126	69.58	0.092
AE	35	57.14	0.132
AK	49	67.62	−0.080
TK	126	49.21	−0.022
ET	90	58.74	0.098
Overall	426	60.02	0.187

After completing the calculation and analysis of network indicators for each construction stage, the six questionnaire respondents were contacted again. The main stage-specific analytical results and corresponding energy-saving management measures were presented to them to assess their consistency with actual on-site construction conditions and to obtain feedback on the rationality and feasibility of the proposed measures. The respondents indicated that the main analytical findings were generally consistent with actual site conditions and that the proposed energy-saving management measures were reasonable and practically feasible. This feedback provided supplementary qualitative support for the practical applicability of the research findings.

4.3. Five-Stage "A-T-E-K" Meta-Network Presentation

Using ORA software, the integrated "A-T-E-K" meta-network across the five construction stages was visualized, as shown in Figure 5. The results illustrate stage-specific differences in the organization's internal resource network. The agent nodes, representing project participants, remain relatively stable across stages, indicating continuity in the main responsible actors. By contrast, variations in task nodes and their associated energy and knowledge nodes and links reflect differences in resource coordination structures across construction stages. For clarity, the five construction stages are hereafter referred to as Stage 1 to Stage 5, corresponding to pipeline relocation and traffic diversion (Stage 1), retaining structure construction (Stage 2), earth excavation (Stage 3), main structure construction (Stage 4), and traffic restoration (Stage 5).

In Stage 1, the network mainly comprises compliance-oriented preparatory tasks. In Stages 2 and 3, the introduction of tasks such as BIM simulation (T15), specialized earthwork recycling (T01 and T02), and innovative construction techniques (T16–T18) increases network complexity. The overall network density is defined as the ratio of observed links to the maximum possible links across the five relationship types (AT, AE, AK, ET, and TK) [88]. The overall network density values for Stages 1–5 were 0.712, 0.715, 0.686, 0.667, and 0.686, respectively. Stage 2 exhibited the highest network density (0.715). Although Stage 4 had the largest number of observed links (246), its greater number of task nodes increased the maximum number of possible links to 369, resulting in the lowest overall network density (0.667). In Stage 5, the number of observed links decreased to 162, reflecting a reduction in the number of task-related resource associations.

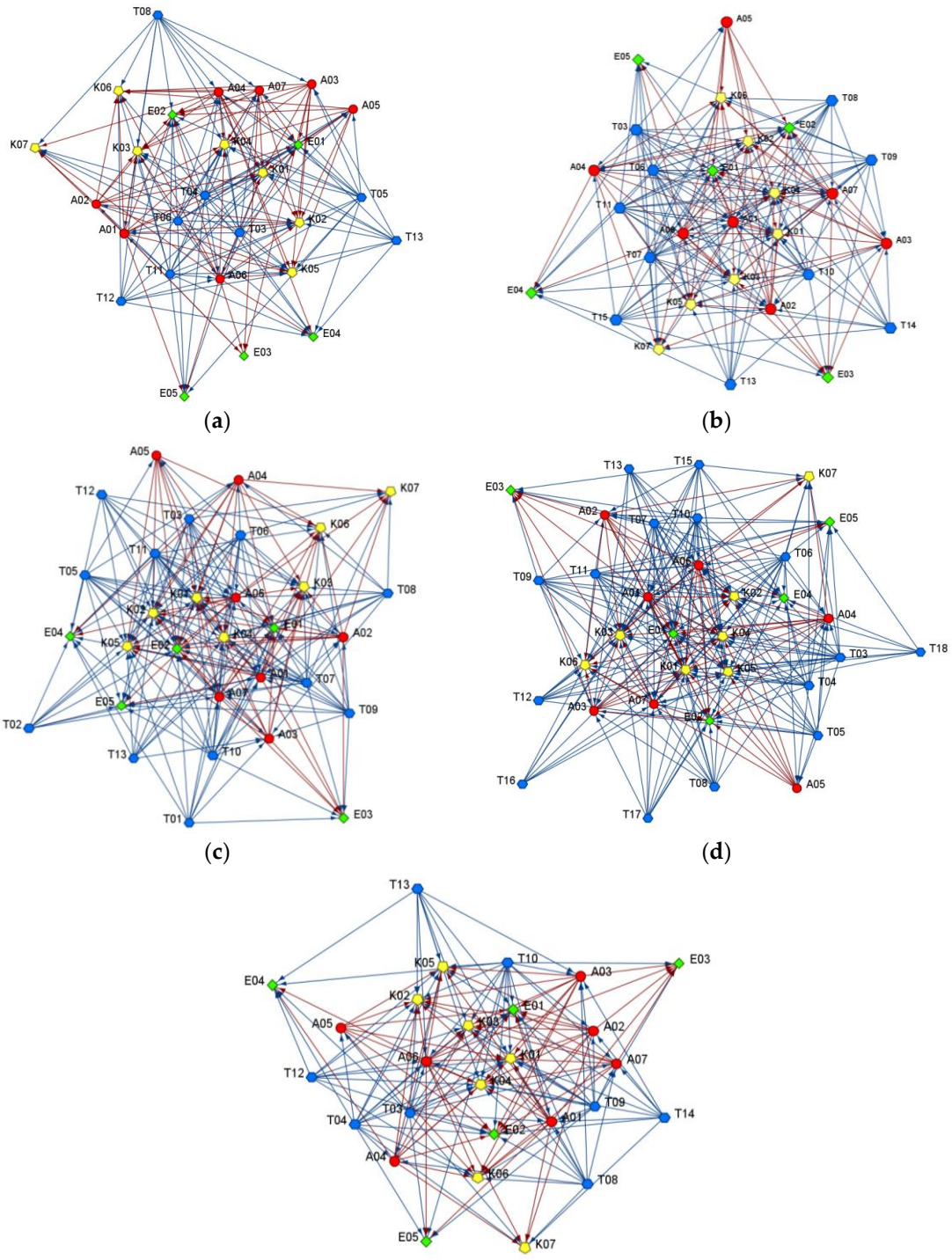


Figure 5. Evolution diagram of the five-stage "A-T-E-K" meta-network: (**a**) meta-network in Stage 1; (**b**) meta-network in Stage 2; (**c**) meta-network in Stage 3; (**d**) meta-network in Stage 4; (**e**) meta-network in Stage 5.

4.4. Quantifying the Energy-Saving Capability of Metro Construction in Ecologically Sensitive Areas

This section calculates and analyzes the indicators of the five-stage "A-T-E-K" meta-network to examine the application of the proposed framework and identify stage-specific priorities for organizational energy-saving management. From the perspective of RDT, it quantifies internal network relationships to examine how the organization manages

external legitimacy dependence and to identify management shortcomings across different construction stages.

4.4.1. Task–Energy Demand Matching Degree Results

The TE indicator shows clear fluctuations across the five stages, as illustrated in Figure 6. In Stage 1 (TE = 1.00), the complete match within the constructed network indicates a high degree of structural alignment between task-related energy requirements and available energy-control relationships during project initiation. The marked decline in Stage 3 (TE = 0.75) indicates greater mismatches between task-related energy requirements and energy-control relationships during earth excavation, which may be associated with the increased complexity of construction activities and resource coordination at this stage. This result highlights the need for closer coordination between task requirements and energy-control relationships during this stage. The subsequent recovery in the later stages, reaching TE = 0.95 in Stage 5, indicates improved structural alignment between energy-saving tasks and energy-control relationships within the network. From the perspective of RDT, this improvement reflects a more favorable alignment between task-related energy requirements and internal energy-control relationships in the later construction stages. Overall, the evolution of the TE indicator reveals stage-specific differences in the organization's internal resource coordination, highlighting the importance of aligning energy-related resources with changing construction requirements.

4.4.2. Energy Omega Results

The EO indicator fluctuates across the five stages, as illustrated in Figure 6, reaching its highest value in Stage 4 (EO = 0.894). This result indicates a higher degree of repeated associations between energy-related resources and construction tasks during the main structure construction phase, reflecting the structural characteristics of energy-resource coordination at this stage. By contrast, the lower value in Stage 2 (EO = 0.758) suggests a lower degree of repeated associations between energy-related resources and construction tasks during retaining structure construction. From the perspective of RDT, these stage-specific differences reflect variations in the configuration of energy-resource dependencies within the project network, rather than the physical reuse of energy or construction materials.

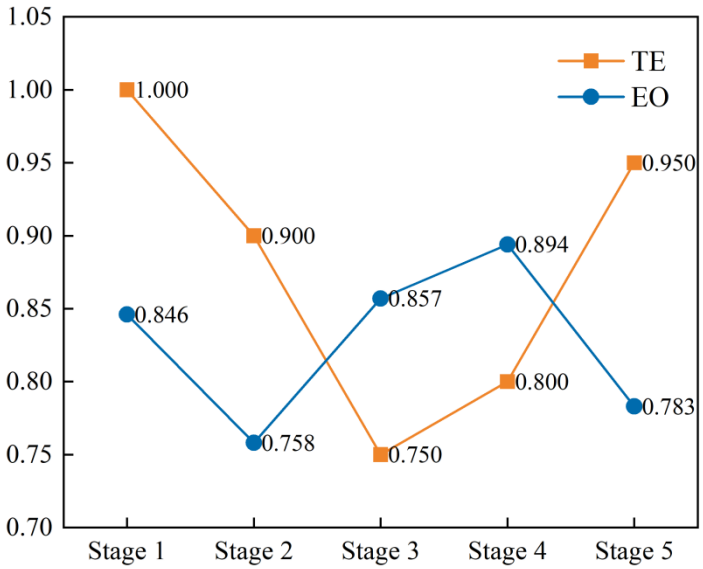


Figure 6. Line graph showing changes in TE and EO over five stages.

Taken together, the TE and EO results highlight stage-specific differences in the structural organization of energy resources during metro construction. Higher TE values in the initial and final stages indicate stronger task–energy matching within the network, whereas variations in EO reflect differences in the repeated associations between energy types and construction tasks. These findings suggest that energy-resource coordination should be adapted to the requirements of different construction stages. For example, during earth excavation, greater attention should be paid to identifying and addressing task–energy mismatches, while during retaining structure construction, managers should examine common energy-resource dependencies across tasks to identify opportunities for improved coordination.

4.4.3. Agent–Energy Control Compatibility Results

The AE_i values and their changes across the five construction stages are shown in Figure 7. The results show that the mean AE_i value across the seven agents increased from 0.678 in Stage 1 to 0.742 in Stage 5, representing a rise of 9.4%. This trend indicates that, as the project progressed, most participating agents, including the Construction Management Unit (A01), Supervision Unit (A02), Design Unit (A03), Equipment Supplier (A04), and Construction Team (A07), exhibited improved structural compatibility between their task-related energy requirements and energy-control relationships. In particular, the Government Regulatory Authority (A06) maintained an AE_i value of 1.0 throughout all stages, indicating complete alignment between its task-related energy requirements and the corresponding control relationships represented in the network. By contrast, the Energy Service Company (A05) remained at a relatively low level (0.5) across all stages, suggesting a persistent structural mismatch between its task-related energy requirements and energy-control relationships. These differences highlight variations in the structural alignment between task-related energy requirements and energy-control responsibilities among project participants.

The evolution of AE_i is consistent with the logic of resource dependence theory, as it reflects changes in how project organizations align task-related energy requirements with internal energy-control relationships under external constraints. Overall, the participating agents displayed a positive trend in network-based energy-control compatibility during metro construction in ecologically sensitive areas. Most actors exhibited improved structural alignment through internal resource coordination. This improvement became more evident in the later project stages, particularly in Stage 5, suggesting a stronger organizational basis for managing energy-resource dependencies rather than directly demonstrating reductions in energy consumption.

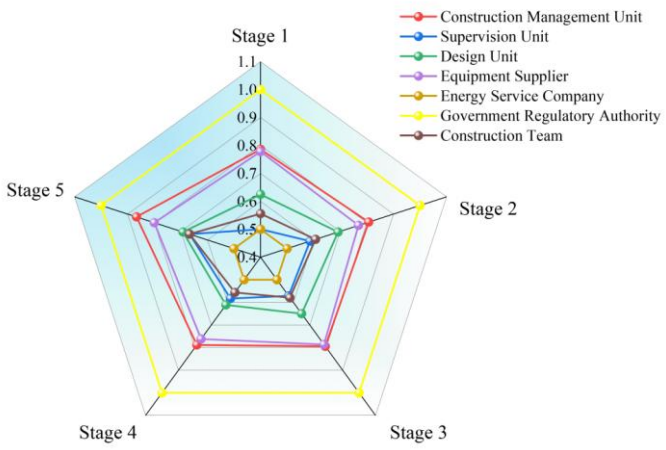


Figure 7. Agent–Energy Control Compatibility of five stages.

4.4.4. Task–Knowledge Demand Deviation Results

The TK_i values and their changes across the five construction stages are shown in Figure 8. The results indicate that the completeness and specificity of knowledge resources are critical for translating external requirements into effective internal action. The average TK_i value fluctuates within a narrow range of 0.075–0.095, suggesting relatively limited knowledge-demand deviations within the constructed network. However, knowledge demand differs across participants. The Construction Management Unit (A01), Supervision Unit (A02), Equipment Supplier (A04), and Government Regulatory Authority (A06) show $TK_i = 0$, indicating no identified task–knowledge gap under the network-based assessment. By contrast, the Design Unit (A03), Energy Service Company (A05), and Construction Team (A07) display varying levels of deviation, with the Energy Service Company (A05) consistently exhibiting relatively high TK_i values. This pattern suggests a persistent mismatch between task-related knowledge requirements and available knowledge resources, indicating a potential need for additional technical support.

The highest TK_i value appears in Stage 2, which corresponds to technically demanding activities such as retaining structure construction. This result indicates that knowledge integration becomes more difficult when legitimacy pressure is concentrated in specialized technical areas. Overall, the network results suggest relatively limited task–knowledge deviations, although structural differences remain among participating agents. In particular, some participants, especially the Energy Service Company (A05), exhibit greater mismatches between task-related knowledge requirements and available knowledge resources, which may constrain organizational energy-saving capability. Although the network-based alignment improves in the later stages, targeted training and technical support may help address the identified knowledge-resource mismatches and support compliance-related tasks in ecologically sensitive metro construction.

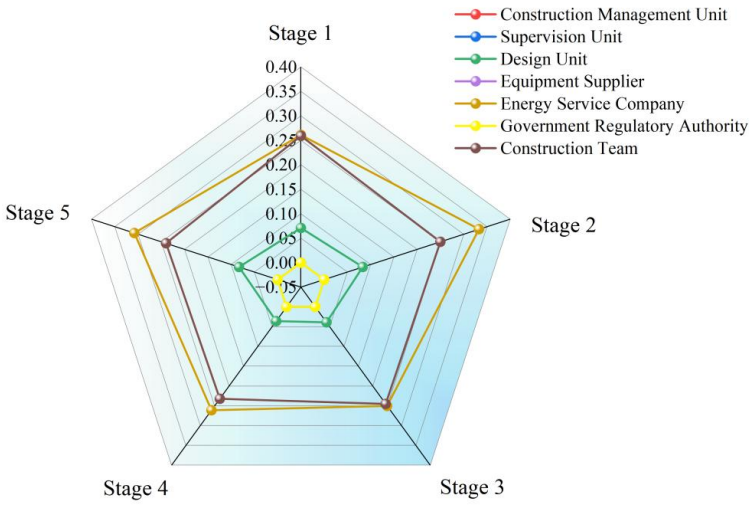


Figure 8. Task–Knowledge Demand Deviation of five stages.

5. Discussion

5.1. Meta-Network-Enabled Construction Management for Enhancing Energy-Saving Capability

This study develops a meta-network model integrating agents, tasks, energy, and knowledge to assess and enhance the energy-saving capability of project organizations through coordinated resource management. Unlike conventional approaches, which mainly focus on total energy consumption or retrospective performance accounting [89], the proposed "A-T-E-K" framework provides a structured way to translate the external requirement for construction legitimacy, an important concern in RDT, into a set of

manageable internal variables. This is achieved through specific network parameters that are often absent from traditional assessment methods. Compared with conventional stage-based evaluations in metro construction, which usually rely on fixed assessment boundaries, the proposed meta-network model captures stage-specific variations in resource relationships across construction stages [90]. In particular, it enables project organizations to identify resource dependencies and coordination patterns more systematically, thereby supporting the management of compliance-related risks associated with energy use [91]. This approach can reduce dependence on new external resources and help limit ecological disturbance in metro construction projects located in ecologically sensitive areas. In addition, unlike multi-level indicator systems that rely on subjective weighting [92], or machine learning methods that require large amounts of historical data and predefined prediction parameters [93], the proposed model helps identify potential organizational capability gaps by measuring relational misalignments within the project system, such as mismatches between tasks and knowledge. This makes it possible to detect specific capability gaps among responsible actors, including insufficient technical knowledge or weak resource control. As a result, potential compliance risks can be addressed through targeted interventions, such as training, knowledge transfer, scheduling adjustment, and improved resource sharing. More broadly, the model supports a shift from reactive compliance to proactive construction management and capability building in metro construction projects in ecologically sensitive areas. By revealing structural disconnections and visualizing differences across construction stages, it provides a basis for targeted management actions and continuous optimization. Through this integrated process of diagnosis, attribution, and improvement, the framework helps managers strengthen the internal resource base of project organizations and secure the external legitimacy required for successful project implementation.

The above case-study findings also provide exploratory evidence for the two research propositions proposed in this study. Regarding Proposition 1 (P1), Task–Energy Demand Matching Degree (TE) reached its lowest value of 0.75 during earth excavation, whereas Energy Omega (EO) peaked at 0.894 during main structure construction. Together with the stage-specific changes in construction tasks and resource relationships, these results indicate distinct patterns of task–energy matching and energy-resource relationship structures across construction stages, consistent with P1. Regarding Proposition 2 (P2), the Government Regulatory Authority (A06) maintained an Agent–Energy Control Compatibility (AE_i) value of 1.0 throughout all five stages, whereas the Energy Service Company (A05) remained at 0.5, indicating differences in structural compatibility among project agents. Meanwhile, the Construction Management Unit (A01), Supervision Unit (A02), Equipment Supplier (A04), and Government Regulatory Authority (A06) exhibited no identified task–knowledge gaps, while other agents showed varying levels of Task–Knowledge Demand Deviation (TK_i). These findings reveal agent-specific differences in energy-control compatibility and knowledge-demand deviation, consistent with P2.

Recent studies have provided important insights into the environmental performance of metro construction. Shinde et al. [94] applied life-cycle assessment to quantify the environmental impacts of underground metro systems, while Kong et al. [95] evaluated construction-related carbon emissions through comparisons of metro station construction methods. Although these approaches provide quantitative evidence of environmental impacts and emission reduction potential, the proposed A–T–E–K framework offers a complementary perspective by examining how organizational resource relationships support energy-saving management. From a stakeholder-network perspective, Xu et al. [96] demonstrated the importance of interactions among stakeholder-associated factors in building energy performance. Building on this perspective, the A–T–E–K framework integrates agents, tasks, energy-related resources, and knowledge to identify

structural mismatches and stage-specific resource dependencies. Furthermore, Zhang et al. [97] demonstrated the potential of digital twins for real-time monitoring and multi-objective optimization in tunnel construction. Integrating operational monitoring data with periodically updated meta-networks may therefore provide a promising direction for further examining the relationship between organizational resource coordination and actual energy performance.

5.2. Strategies to Enhance Energy-Saving Capability

Metro construction involves stage-specific variations in energy use, stakeholder responsibilities, and ecological risks, requiring tailored management strategies. Such strategies can better align internal resource coordination with the external pressures faced at each stage. Based on the proposed energy-saving capability assessment framework, this study develops stage-specific strategies to support a shift from reactive compliance toward proactive energy-saving capability development. As the case project used both electric and conventional fuel-powered equipment, these strategies address the coordination of multiple energy types rather than exclusive reliance on electricity. The underlying management principles, including resource allocation, task–energy matching, stakeholder coordination, and knowledge support, may also be applicable to conventional metro construction projects, provided that specific measures are adapted to their equipment configurations, energy structures, and environmental requirements.

(1) Pipeline relocation and traffic diversion stage: Supporting organizational decision-making through a digital twin-based dependency internalization system.

At this stage, the priority is to establish a project-level digital decision platform. By integrating BIM and GIS technologies, external constraints, such as ecological protection boundaries and underground utility network data, can be incorporated into a virtual simulation environment [98]. This enables project organizations to translate complex approval and coordination risks into measurable internal indicators, such as a comprehensive disturbance index and baseline energy budget, thereby identifying an optimal energy-use path at the outset.

(2) Retaining structure construction stage: Implementing closed-loop management through task–knowledge coordination.

The key task at this stage is to establish a proactive mechanism for addressing knowledge gaps. By using the meta-network framework to monitor the alignment between task knowledge requirements and the knowledge available among project participants, the organization can trigger timely interventions, such as targeted training or process improvement, when critical gaps are identified [99]. This training should cover not only energy-saving techniques, but also environmental protection practices specific to ecologically sensitive areas. In this way, dependence on external technical expertise is gradually transformed into an internal and planned learning process.

(3) Earth excavation stage: Deploying data-driven dynamic resource scheduling.

At this stage, management should focus on building a real-time optimization system based on IoT data and algorithmic scheduling. By linking equipment sensor data with external information, such as traffic conditions and disposal site availability, the project organization can optimize excavation sequences and transport routes in real time [100]. This approach allows external uncertainty to be incorporated into an internally manageable scheduling system, reducing idle energy consumption and limiting the duration and intensity of local air and noise impacts.

(4) Main structure construction stage: Optimizing multi-actor coordination and energy-resource management.

This stage requires stronger coordination among project participants and more efficient energy use within the site. One strategy is to identify and strengthen key coordination actors through meta-network analysis, thereby improving overall network resilience and collaborative efficiency [101]. Another is to establish a site-level energy micro-circulation system by introducing photovoltaic generation, energy storage, and waste heat recovery technologies. These measures can reduce reliance on external energy supply, improve energy autonomy, and better align project implementation with ecological protection requirements and sustainability expectations.

(5) Traffic restoration stage: Promoting the reuse of digital assets and organizational knowledge.

At the final stage, the priority is to preserve and reuse the knowledge generated during the project. A digital asset package can be developed by linking key performance data to BIM-based construction scenarios and storing them in a credible digital archive [102]. Such an archive could support the documentation and verification of environmental compliance and disturbance reduction, provided that relevant monitoring data are available. At the same time, meta-network analysis results, management procedures, and intervention strategies can be consolidated into a standardized diagnostic toolkit. In this way, the pressure associated with final acceptance and the risk of knowledge loss can be converted into reusable organizational assets that support future projects.

6. Conclusions and Limitations

Based on RDT, this study develops an "A-T-E-K" meta-network framework to assess and enhance the energy-saving capability of metro construction projects in ecologically sensitive areas through coordinated resource management. Using Wuxi Metro Line 5 as a case study, the results reveal stage-specific differences in resource coordination among agents, tasks, energy, and knowledge under external ecological and regulatory constraints. The main findings are as follows: (1) the network-based indicators exhibit clear stage-specific variations, with task–energy matching reaching its lowest level during earth excavation and repeated task–energy resource associations reaching their highest level during main structure construction; (2) the diagnostic indicators AE_i and TK_i help identify structural mismatches in energy-control relationships and knowledge resources, thereby providing a basis for targeted management improvement. The theoretical contribution of this study lies in applying RDT to interpret the coordination of task-related energy resources and knowledge across project participants under ecological legitimacy constraints. By examining these relationships within the A–T–E–K meta-network, the study provides a structural perspective on stage-specific resource dependencies in metro construction. From a practical perspective, the proposed framework provides project managers with a systematic tool to diagnose coordination deficiencies, optimize resource configuration, and strengthen energy-saving capability, thereby supporting ecological compliance and construction legitimacy in ecologically sensitive areas.

The findings of this study should be interpreted in light of three limitations. First, the identification of nodes and relationships relied partly on expert judgment, introducing potential subjectivity into meta-network construction. Although inter-rater agreement was assessed, it was limited. In addition, binary relationships capture only the presence or absence of connections without reflecting their strength, while stage-specific static networks cannot fully represent the evolution of interactions among agents, tasks, energy resources, and knowledge during construction. Future studies could adopt more structured expert elicitation and disagreement-resolution procedures, weighted relationships, and time-series data for dynamic network analysis. Second, the case project combined electric and conventional fuel-powered equipment under specific ecological constraints,

which may differ from those of other metro construction projects. Therefore, the proposed stage-specific strategies may require adaptation to different energy configurations and ecological conditions. Future studies could examine their applicability through multiple case studies to further validate and refine the framework. Third, the four indicators primarily capture structural aspects of energy-saving capability rather than directly measured energy-saving outcomes. Although they help identify resource coordination patterns and potential management weaknesses, their relationships with actual energy consumption and energy savings were not empirically tested due to the limited availability and comparability of project-level energy-consumption records. Future research should incorporate standardized energy-consumption data from comparable construction activities to assess the empirical validity of these indicators.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and was approved by the Specialized Committee for Scientific Research of Nanjing Tech University (protocol code NTJTECH-1-66; date of approval: 20 April 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

A-T-E-K	Agents–Tasks–Energy–Knowledge
BIM	Building Information Modeling
EU	European Union
GIS	Geographic Information System
IoT	Internet of Things
LED	Light-Emitting Diode
MNA	Meta-Network Analysis
ORA	Organizational Risk Analyzer
RDT	Resource Dependence Theory

Appendix A

Table A1. Nodes in the "A-T-E-K" meta-network of a metro construction project.

Node Types	Number	Nodes
Agent	A01	Construction Management Unit
	A02	Supervision Unit
	A03	Design Unit
	A04	Equipment Supplier
	A05	Energy Service Company
	A06	Government Regulatory Authority
	A07	Construction Team
Task	T01	Optimize the design of excavation and filling balance to reduce the secondary transportation of earthwork in the site
	T02	Classify excavated soil and recycle usable materials
	T03	Replacing fuel equipment with electric machinery
	T04	Rational placement of charging piles and energy storage for load balancing
	T05	Install solar panel power systems and dedicated energy supply zones
	T06	Implement LED energy-efficient lighting
	T07	Reduce material waste (e.g., optimize formwork turnover) and production energy consumption
	T08	Rational deployment and regular maintenance of mechanical equipment
	T09	Water resource recycling
	T10	Waste material recycling
	T11	Use energy-saving building materials
	T12	Implement real-time energy monitoring systems
	T13	Off-peak electricity usage to reduce grid load
	T14	Optimize piling sequence to minimize machinery idle time
	T15	Simulate construction processes using BIM to reduce rework and machinery downtime
	T16	Replace welding with sleeve extrusion connections/straight-thread couplers to cut power use and pollution
	T17	Adopt cold-applied membranes over hot-melt methods to reduce gas/electricity consumption
	T18	Recycle waterproofing membrane scraps for joint filling/repairs
Energy	E01	Electric energy
	E02	Fossil fuels (diesel, gasoline, coal)
	E03	Water Resources
	E04	Thermal Energy
	E05	Renewable Energy
Knowledge	K01	Energy-saving technology
	K02	Energy Management Standards
	K03	Risk Control & Emergency Response Plans
	K04	Data Analysis & Decision Support
	K05	Policies, Regulations & Compliance Requirements
	K06	Training & Skill Enhancement
	K07	Collaboration Mechanisms & Agreements

Note: The E-node category includes both energy sources and energy-related resources. Water Resources (E03) are included because water-management activities, such as pumping and recycling, involve energy consumption; water itself is not classified as an energy source.

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