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PRACTICAL APPLICATION OF AGENT-BASED MODELING TO ASSESS THE EFFICIENCY OF COMMUNICATION NETWORKS IN CONSTRUCTION PROJECTS

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ABSTRACT

The article is dedicated to explaining how communication efficiency in construction project networks forms through interaction-driven structural change. Relevance emerges from the growing mismatch between rigid coordination models and the fluid nature of communication in distributed project environments. Scientific novelty is associated with interpreting communication networks as adaptive systems in which efficiency depends on internal transformation rather than static structure. The work describes how interaction parameters reshape network configurations and how these configurations alter coordination regimes. Special attention is paid to threshold conditions under which communication patterns reorganize. The work sets a goal to explain the mechanisms linking interaction rules with structural outcomes. Analytical synthesis, comparative examination, and conceptual modeling are used to address this problem. A set of recent studies and empirical configurations has been examined to identify recurring patterns of interaction and transformation. The conclusion describes how communication efficiency depends on structural adaptability and alignment between interaction conditions and network configuration. The article will be useful for researchers and practitioners working with complex coordination systems.

KEYWORDS: agent-based modeling, communication networks, coordination efficiency, network dynamics, structural transformation, heterogeneity

INTRODUCTION

Communication in construction projects unfolds within systems where interaction patterns evolve during execution rather than remain fixed. Information moves across multiple layers, connecting participants through temporary and shifting pathways. These pathways form structures that change as interaction conditions vary. Static descriptions capture connectivity at a given moment. They do not explain how coordination takes shape.

Analytical attention often focuses on measurable properties such as density or centralization. These properties describe structure. They do not reveal how structure forms. Interaction rules remain implicit. As a result, communication efficiency is frequently interpreted through static indicators rather than through processes that generate them.

The purpose of this study is to explain how interaction mechanisms shape communication efficiency through structural transformation of networks. To achieve this purpose, three research objectives are defined:

1) to analyze how interaction parameters influence the formation of network structures;
2) to identify mechanisms linking heterogeneity, composition, and coordination dynamics;
3) to evaluate how different structural states affect communication efficiency.

The hypothesis assumes that communication efficiency emerges from the interaction between agent behavior, structural configuration, and parameter thresholds governing structural transitions.

Scientific novelty is associated with addressing a gap between structural descriptions and process-based explanations. Previous studies examine interaction, relational properties, or structural forms separately. Their interdependence remains insufficiently clarified. The present work interprets communication networks as systems in which structure, interaction, and coordination evolve together.

METHODS AND MATERIALS

Literature was assembled through targeted retrieval from international scientific databases, including Scopus, Web of Science, and engineering-focused repositories, with emphasis on publications from the last five years. Search logic relied on combining keyword clusters through logical operators, linking categories of interaction processes, structural configurations, and coordination dynamics. This approach made it possible to capture studies that describe systems as sets of interacting elements rather than isolated variables.

The initial pool comprised approximately forty sources and was reduced to a focused set of analytically relevant studies through iterative filtering. Selection did not prioritize thematic similarity. It prioritized the ability of a source to expose relationships between elements, describe implementation detail, and reveal how processes unfold across multiple layers. Works limited to static structural indicators without process explanation were excluded at later stages of screening.

The analytical design combines structured review with conceptual interpretation of underlying relationships. Retrieved studies describe different types of systems. Some reconstruct interaction environments in which local rules generate observable structural patterns. Others examine empirical configurations, identifying properties such as connectivity distribution, interaction intensity, or relational stability. A separate group addresses technological infrastructures that capture and transmit interaction data in real time.

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Across these directions, recurring mechanisms become visible. Interaction preference shapes connection patterns. Influence propagation redistributes connectivity across nodes. Structural reinforcement stabilizes configurations through repeated interaction. Adaptive reconfiguration alters system form when interaction conditions change. These mechanisms are identifiable in most studies, yet they are rarely examined as interdependent processes. Structural descriptions often omit relational dynamics. Empirical observations capture relationships but do not explain how structures transform.
The reviewed material demonstrates substantial heterogeneity in analytical depth and focus. Some studies emphasize algorithmic representation of interaction. Others concentrate on observable patterns without reconstructing underlying processes. This variation provides multiple partial explanations. It does not produce a unified interpretation.

Comparison of these sources reveals a consistent limitation. Structures, interactions, and outcomes are typically examined separately, while their interdependence remains insufficiently clarified. As a result, systems are interpreted as collections of components rather than as internally connected processes. This gap leads directly to the present study, where communication networks are analyzed as integrated systems in which interaction rules, structural transformations, and coordination effects evolve together.

RESULTS

Communication efficiency in construction project networks does not stabilize around a fixed structural configuration; it emerges through continuous reorganization driven by interaction rules embedded at the agent level. The empirical baseline underlying the simulation reflects a structurally asymmetric configuration consisting of 8 central actors embedded within a periphery of 71 nodes, representing a specific observed project communication network rather than a generalized structural model. Coordination pathways concentrate through this limited subset of intermediaries, and the network inherits a dependency structure in which peripheral actors access information primarily through these central positions (Pidiha, 2021).

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Table 1 Structural configurations of communication networks under varying interaction conditions

Network configuration	Interaction mechanism	Structural characteristics	Coordination logic	System-level effect
Core–periphery	Homophily (low α)	Dense central core, sparse periphery	Centralized routing	Stable but dependent coordination
Multi-centered	Moderate homophily	Several semi-connected cores	Parallel coordination	Increased flexibility, synchronization load
Fragmented clusters	High homophily	Isolated dense subgroups	Local coordination	Loss of system-wide coherence
Distributed network	Heterophily	Evenly distributed ties	Decentralized routing	High resilience, lower cohesion
Hierarchical	Eigenvector centrality	Concentrated influence core	Reinforced hierarchy	Efficient but rigid communication

Source: compiled by the author based on (Pidiha, 2021; Son, 2022; Wang et al., 2023)

When interaction is governed by similarity, structural change follows parameter-sensitive thresholds rather than gradual accumulation. At $\alpha < 0.1$, the network retains a unified core–periphery form with persistent triadic closures. Redundant ties accumulate within the core, while peripheral nodes maintain selective connectivity directed toward central actors (Pidiha, 2021). This configuration produces stable communication cycles where coordination sequences repeat with minimal deviation, constraining variability in task execution and resource exchange.

Increasing the parameter to $\alpha = 0.1$–0.4 under 50% domain difference alters the structural logic rather than extending the existing pattern (Pidiha, 2021). The network reorganizes into multiple coordination centers, each maintaining internal cohesion while sharing limited interconnections. The number of effective hubs increases, yet their functional roles diverge. Communication flows become distributed across these centers, reducing reliance on a single node group, while synchronization demands intensify due to the need to align parallel coordination structures.

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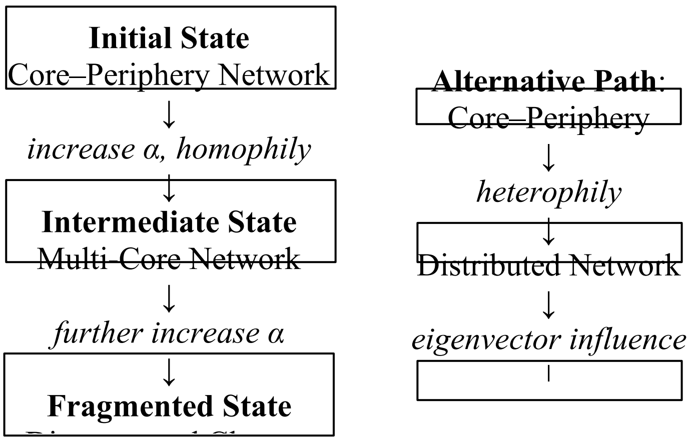
Figure 1. Scheme of communication network transformation under changing interaction parameters



Source: compiled by the author based on (Pidiha, 2021; Mazzetto, 2024; Liu et al., 2024)

At $\alpha > 0.4$, the network ceases to operate as a unified system. Structural segmentation produces distinct subgroups with high internal density and minimal cross-group interaction. Information exchange becomes localized, and coordination no longer propagates across the entire network. Resource allocation aligns with subgroup boundaries, and communication efficiency decreases at the system level despite preserved internal connectivity. The extent of this structural transition depends directly on node heterogeneity. The systematization of approaches is presented below (Table 2).

Table 2. Structural states of communication networks depending on interaction parameter α and heterogeneity

Heterogeneity level	Low α ($\alpha < 0.1$)	Medium α ($0.1 \leq \alpha \leq 0.4$)	High α ($\alpha > 0.4$)
Homogeneous	Stable unified network	Stable unified network	Random structure
Moderately diverse	Core–periphery	Multi-centered network	Semi-integrated network
Highly diverse	Core–periphery	Multi-centered network	Fragmented clusters

Source: compiled by the author based on (Pidiha, 2021)

At 25% domain difference, cohesion persists up to α ≈ 0.8, extending the stability range compared to the 50% configuration, where fragmentation occurs at lower parameter values (Pidiha, 2021). In the limiting case of 0% domain difference, structural integrity is preserved across nearly the entire parameter range and breaks only at α = 1, where the network transitions toward random connectivity.

Variation in agent composition introduces an additional quantitative dimension. In networks with 20 nodes, distributions such as 10/10 (50%) and 5/15 (25%) produce distinct patterns of tie formation (Pidiha, 2021). Balanced distributions amplify subgroup formation, while skewed distributions sustain connectivity through asymmetric interaction probabilities.

Network size modifies these dynamics in a non-linear manner. In configurations exceeding 80 nodes, the frequency of bridging ties increases, allowing communication pathways to persist even under conditions that would otherwise produce fragmentation. In smaller systems, the absence of sufficient bridging nodes leads to rapid structural polarization.

The mechanism used to evaluate node influence alters the distribution of connectivity without changing the underlying interaction rules. When influence is defined through degree centrality, connections accumulate proportionally, and the network retains moderate dispersion in node influence. Replacing this mechanism with eigenvector centrality produces a different structural outcome: nodes connected to influential actors gain additional prominence, leading to a more concentrated hierarchy.

Simulation-based approaches demonstrate that micro-level interaction rules generate coordination regimes that influence project performance, including measurable reductions in delays when interaction structures are optimized (Mazzetto, 2024). The behavior of construction organizations reflects non-linear interaction patterns where minor parameter variations produce disproportionate structural effects, confirming sensitivity of coordination efficiency to underlying network rules (Son, 2022).

Integration of agent-based modeling with digital twin environments and tracking technologies enables precise representation of interaction flows, improving coordination accuracy and resource positioning within project systems (Abdelalim et al., 2024). Empirical analysis shows that cooperation efficiency increases with higher density and reciprocity of trust relationships, while opportunistic behavior disrupts network stability and reduces coordination reliability (Wang and Yin, 2023).

Structural measurements of trust networks identify centralization and cohesion as determining factors of communication performance, linking relational topology with project outcomes (Wang and Yin, 2025). Additional investigation demonstrates that stakeholder characteristics and interaction frequency reshape trust configurations over time, reinforcing the dynamic nature of communication networks (Wang and Yin, 2025).

Longitudinal observations of construction collaboration networks indicate progressive structural integration as interdependence between participants increases, leading to intensified coordination and connectivity (Liu et al., 2024). Analytical frameworks of stakeholder interaction confirm that network configuration influences not only communication efficiency but broader project-level outcomes, including alignment of objectives and reduction of conflict propagation (Yang et al., 2026).

DISCUSSION

Communication networks in construction projects do not function as uniform channels of information exchange; they operate as layered coordination infrastructures in which access, routing, and redistribution of information are structurally differentiated. The presence of a concentrated coordination core embedded within a large periphery introduces an uneven transmission regime. Information does not propagate symmetrically. It is filtered through a limited number of nodes that perform intermediary functions. Peripheral actors do not interact directly with the system as a whole. They connect through intermediaries. This creates latency differences. It shapes decision timing.

Similarity-driven interaction stabilizes communication by reinforcing repeated connection patterns. Dense triadic closure within central regions produces predictable communication loops where the same nodes repeatedly exchange information. Coordination becomes consistent. Variability decreases. At the same time, structural flexibility narrows. Alternative routes are not formed. The system becomes efficient under stable conditions but reacts slowly when interaction demands change. Stability emerges from repetition. It limits adaptation.

As interaction intensity increases, structural organization shifts toward multi-centered coordination. Communication pathways begin to distribute across several node groups rather than concentrating within a single core. These groups process interactions in parallel. Load is redistributed. Communication becomes less dependent on individual nodes. However, synchronization becomes more complex. Information arriving from different centers does not always align temporally. Small delays accumulate. Coordination drifts.

Fragmentation produces a different operational condition. Communication remains active but becomes confined within subgroups. Internal density remains high. External connectivity weakens.

Information circulates efficiently within clusters yet does not extend across the network. Coordination becomes localized. Decisions are made within boundaries that are not aligned with the broader system. The network remains connected in parts. It stops functioning as a whole.

Heterogeneity introduces a structural constraint that determines when such transitions occur. When variation between agents remains limited, interaction opportunities are distributed more evenly across the network. Connectivity persists across a wider parameter range. Once heterogeneity increases, interaction becomes selective. Nodes connect based on similarity thresholds. Structural divergence begins earlier. The system reorganizes sooner. Heterogeneity defines transition points.

Agent composition modifies this behavior in a less visible but equally influential way. The same interaction rules produce different structures depending on how agents are distributed across categories. Balanced compositions increase the likelihood of subgroup formation because interaction probabilities align symmetrically. Skewed distributions disrupt this alignment. Certain nodes begin to connect across categories. These nodes act as intermediaries. They sustain connectivity between otherwise separated groups. Distribution shape's structure.

Network size alters the system through redundancy rather than through scale alone. Larger networks generate additional pathways that compensate for structural constraints. When primary communication routes weaken, alternatives exist. Information is rerouted. Continuity is preserved. In smaller networks, such alternatives are limited. Once connections weaken, fragmentation accelerates. Size changes resilience. It does not simply increase complexity.

The definition of influence restructures how communication pathways form. When influence is based on the number of connections, interaction spreads more evenly across nodes. Influence remains distributed. When influence depends on connection quality, nodes linked to already central actors gain additional prominence. Influence accumulates. Communication pathways concentrate. Hierarchy emerges. Structure follows influence.

These structural configurations translate into different coordination regimes. Distributed networks support parallel information flows. Centralized networks reduce transmission distance but increase dependency on specific nodes. Fragmented networks preserve local efficiency but limit system-wide coordination. None of these regimes is inherently stable. Each operates effectively under specific interaction conditions.

Patterns observed in related studies reflect similar mechanisms. Interaction rules at the micro level generate coordination outcomes that affect project performance. Adjustments in these rules modify communication structures and influence measurable indicators such as delay reduction. Construction organizations exhibit non-linear responses to such adjustments, where small changes in interaction parameters produce disproportionate structural effects. Monitoring technologies introduce a feedback layer. Interaction patterns become visible. Visibility alters behavior. Communication structures can be adjusted in response to emerging imbalances.

Relational dynamics introduce an additional operational layer. Reciprocal connections stabilize communication by reducing uncertainty. Interaction becomes predictable. Opportunistic behavior disrupts this predictability. Some pathways become unreliable. The system compensates by redirecting flows through alternative nodes. Load shifts. Structural pressure increases elsewhere.

Several limitations require consideration. The analysis relies on a simulated environment derived from a single empirical configuration, which constrains the transferability of identified thresholds to other project contexts. Interaction rules are simplified into parameterized forms, while real communication processes involve overlapping organizational, contractual, and temporal constraints. The representation of agent characteristics is reduced to categorical distinctions, which omits behavioral variability present in actual teams. Differences in methodological approaches across existing studies limit direct alignment of structural observations, particularly where alternative definitions of influence and interaction are used.

Earlier research frequently captures network structures at isolated moments, emphasizing static configurations. The current analytical approach focuses on transitions between configurations. This shift changes interpretation. Network efficiency is not associated with a specific structure but with the conditions under which structures reorganize. Observations from digital monitoring studies indicate that communication patterns can be tracked with high temporal resolution, though their implementation depends on technological infrastructure. Studies of trust-based interaction highlight the influence of relational density and reciprocity on cooperation, yet often assume stable interaction environments. Longitudinal analyses of collaborative networks indicate increasing structural integration over time, though the mechanisms of this integration vary across project types.

Communication networks do not converge toward a fixed optimal state. They operate through continuous adjustment. Structural efficiency shifts with interaction conditions, agent distribution, and network scale. Coordination remains conditional.

CONCLUSION

Interaction mechanisms define how communication structures form and transform within project networks. Structural configurations emerge from these interactions and do not remain fixed.

Analysis of interaction parameters shows that increasing intensity redistributes coordination across the network, altering pathways of information flow. Heterogeneity determines when structural transitions occur. Lower variation sustains connectivity. Higher variation accelerates divergence.

Agent composition influences the availability of connections between groups. Network size introduces redundancy, allowing communication to persist under structural change. Influence mechanisms reshape connectivity by concentrating or dispersing interaction depending on structural position.

Each research objective is addressed through identification of these relationships. Interaction parameters explain structural formation. Heterogeneity and composition define transition conditions. Structural states reshape communication efficiency.

Communication efficiency depends on how interaction rules align with structural conditions. It changes as these conditions change.

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