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Modeling the Evolution of Construction Crews' Social Networks as a Practical Tool for Improving Resource Management Efficiency

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Abstract

The article is dedicated to the analysis of how communication networks within construction crews evolve and how these transformations influence resource management efficiency. The relevance of the topic is determined by the increasing complexity of construction projects, where coordination depends not only on formal structures but on dynamic interaction patterns. The novelty lies in interpreting network evolution not as a descriptive characteristic but as an operational mechanism that reshapes resource distribution. The work describes structural configurations of crew networks, examines how interaction rules generate these configurations, and studies their impact on coordination processes. Special attention is paid to the transition between centralized, clustered, and fragmented structures and to the conditions under which these transitions alter system performance. The work sets itself the goal to explain how network evolution can be used as a practical tool for improving resource management efficiency. Agent-based modeling and analytical comparison are used to solve this task. The conclusion describes how efficiency emerges from controlled structural variability. The article will be useful for researchers and practitioners working with complex project coordination systems.

Keywords: *Construction Crews, Social Network Evolution, Resource Management, Agent-Based Modeling, Coordination Systems.*

INTRODUCTION

Coordination in construction projects is often interpreted through formal hierarchies and predefined workflows. At the same time, real communication processes form distributed interaction networks that reshape how decisions circulate. These networks do not remain static. They reorganize as tasks evolve, roles shift, and interaction preferences change. Their structure influences how resources are allocated. In many cases, inefficiencies emerge not from the absence of communication but from its configuration.

Existing studies describe communication patterns or propose modeling approaches, yet they rarely explain how network structure transforms operational behavior. Analytical attention is frequently directed either to interaction rules or to performance outcomes. The internal mechanism linking these elements remains insufficiently articulated. Structural transitions are observed. Their role in resource management is not consistently interpreted as a controllable process.

The purpose of the study is to develop a conceptual and simulation-based model that enables the regulation of network evolution in construction crews in order to improve resource management efficiency. Three research objectives follow from this purpose.

1) to analyze structural configurations emerging in construction crew networks under varying interaction rules.
2) to identify mechanisms through which these configurations reshape communication pathways and resource flows.
3) to model the conditions under which structural transitions enhance or degrade coordination efficiency.

The hypothesis assumes that resource management efficiency depends not on a fixed network structure but on the system's ability to maintain controlled transitions between structural states. When such transitions are regulated, coordination remains adaptive. When they are constrained or uncontrolled, inefficiencies accumulate.

The novelty of the study lies in integrating agent-based modeling with dynamic structural regulation principles, enabling the transition from descriptive network analysis to prescriptive coordination management.

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METHODS AND MATERIALS

The methodological construction follows a comparative and interpretive trajectory rather than a predefined procedural template. Descriptions of communication in construction crews encountered in recent literature do not align into a single explanatory model. They diverge depending on how interaction is conceptualized. Some studies simulate coordination through agent-based frameworks where individual decisions generate emergent network structures. Others capture communication as relational snapshots using social network metrics. A third group embeds interaction patterns into project management environments, linking them to performance indicators. These representations describe the same system under different analytical lenses. Their coexistence reveals a discontinuity in how network evolution is understood.

The empirical basis of the analysis was formed from publications indexed in Scopus, Web of Science, and IEEE Xplore, with preference given to open-access journal articles that provide access to implementation details. The temporal range was limited to 2021–2025 in order to retain methodological relevance. Search logic was constructed through intersecting keyword clusters combining "construction crews" with "social networks," "agent-based modeling," "network evolution," and "resource management," linked through AND/OR operators. The configuration was adjusted iteratively. The objective was not to maximize retrieval volume but to capture intersections between modeling approaches and applied coordination contexts. Approximately forty sources were identified at the initial stage.

Filtering reduced this set through consecutive analytical steps. Duplicate records were removed first. Screening based on titles and abstracts followed, excluding studies that treated communication as a static attribute or did not represent interaction dynamics. Full-text assessment further narrowed the corpus by eliminating works lacking operational interpretation of coordination processes or those detached from construction or comparable multi-agent environments. The final sample consisted of thirteen studies. The resulting corpus remains heterogeneous. This heterogeneity is preserved intentionally, as it enables comparison across different methodological positions.

Selection was guided by analytical relevance rather than formalized criteria labels. Studies were retained when they described mechanisms through which interaction rules generate network structures or when they linked structural configurations to coordination outcomes and resource distribution. Works limited to descriptive metrics without dynamic modeling, as well as studies lacking system-level interpretation, were not included. The retained studies differ in depth and technical orientation. This variation allows the analytical procedure to move across perspectives rather than remain confined within a single methodological domain.

Within the selected corpus, several intersecting analytical directions can be identified, though their boundaries remain fluid. Agent-based modeling studies describe how local interaction rules produce structural patterns such as clustering, centralization, and fragmentation, revealing strong sensitivity of network topology to parameter variation. Social network analysis approaches capture properties such as density, centrality, and subgroup formation, linking them to coordination efficiency but often without modeling temporal evolution. Applied studies integrate communication structures into project environments, demonstrating how interaction patterns influence task execution and resource allocation, though frequently under simplified assumptions regarding network formation. These directions do not contradict each other. They describe different layers of the same system. Their integration remains incomplete.

Comparison across these approaches reveals a recurring limitation. Interaction rules, structural configurations, and resource management outcomes are typically examined as separate analytical elements. The transformation connecting them is not consistently reconstructed. Communication is described as exchange. Structure is described as configuration. Efficiency is described as outcome. The process through which network evolution reshapes resource flows remains only partially articulated. As a result, network change is often treated as a by-product of coordination rather than as an operational mechanism.

This limitation becomes more visible when construction crew coordination is interpreted as a dynamic system. Interaction patterns evolve continuously, altering communication pathways and redistributing decision flows. These changes precede observable performance effects. Existing studies capture individual segments of this process but do not fully explain their interdependence. The gap lies not in empirical evidence but in the absence of a unified interpretive framework capable of linking network evolution to resource management efficiency.

The analytical procedure addresses this gap through the integration of comparative analysis, synthesis, and conceptual modeling. Comparative analysis was used to identify differences in how interaction mechanisms and structural effects are represented across studies. Synthesis enabled consolidation of recurring patterns into a coherent analytical structure. Conceptual modeling allowed these patterns to be interpreted as components of a dynamic coordination system in which network evolution functions as an operational parameter influencing resource distribution. The resulting methodological framework does not replicate existing models. It reconstructs their underlying logic through comparison.

RESULTS

Communication structures observed in construction crews do not merely reorganize under interaction rules; they produce operational regimes that can be directly translated into management decisions. The initial empirical configuration—8 highly connected actors embedded within a periphery of 71 nodes—already defines a constrained coordination topology in which decision flow is routed through a limited set of intermediaries (Pidiha, 2021). Such concentration stabilizes early-stage coordination but simultaneously introduces dependency. Resource allocation follows shortest communication paths. Disruptions at central nodes propagate rapidly. The system remains efficient while load remains within the processing capacity of the core.

When interaction preferences shift toward similarity, the redistribution of ties follows a predictable trajectory. At α values below 0.1, the network maintains a unified core-periphery structure with triangular closures, indicating localized redundancy in communication channels. This configuration supports stable task execution where repeated interactions reinforce coordination routines. In operational terms, this regime corresponds to standardized workflows where crew members rely on familiar interaction patterns. Intervention at this stage is unnecessary. The system self-stabilizes.

A different configuration emerges as α approaches the interval 0.1–0.4 under 50% domain heterogeneity (Pidiha, 2021). The appearance of either a single reinforced core or two partially connected cores indicates the beginning of structural duplication of coordination centers. Decision authority becomes distributed but not yet fragmented. This is the point where resource management gains flexibility. Parallel coordination channels appear. However, synchronization costs begin to accumulate. At this stage, management intervention becomes selective rather than corrective: cross-core communication must be maintained deliberately to prevent divergence in task execution.

The transition becomes critical when α exceeds 0.4 and approaches 1. The system reorganizes into distinct subgroups with limited interconnection. Communication paths elongate. Resource flows become localized within clusters. Under these conditions, coordination delays are not caused by lack of communication but by its structural segmentation. The implication is operationally precise: once subgroup formation stabilizes, resource allocation must be externally synchronized. Without intervention, each subgroup optimizes locally while degrading overall project efficiency.

The same mechanism behaves differently when domain heterogeneity decreases to 25%. The persistence of a unified core-periphery structure up to α≈0.8 indicates that partial diversity maintains structural cohesion even under strong similarity preference (Pidiha, 2021). This configuration provides a broader safe operating range. Communication remains globally connected while allowing localized specialization. In practice, such systems correspond to crews where roles differ but overlap sufficiently to sustain cross-functional interaction. Management can tolerate higher clustering without risking fragmentation.

In fully homogeneous configurations (0% domain difference), structural integrity remains intact across almost the entire parameter range. Fragmentation appears only at α=1, where random structures replace coordinated patterns . This behavior reflects the absence of structural drivers for subgroup formation. Coordination remains stable but rigid. Adaptation capacity decreases. Resource allocation becomes predictable but less responsive to changing conditions. Such systems perform reliably under stable workloads but degrade under variability.

The replacement of degree centrality with eigenvector centrality modifies how influence propagates through the network. Nodes connected to already influential actors gain disproportionate weight, accelerating the formation of dominant coordination hubs. Structural consolidation occurs earlier. Bottlenecks appear sooner. This shift has direct managerial implications: monitoring only the number of connections is insufficient. The quality of connections—who is connected to whom—determines how quickly control centralizes.

Heterophily-driven interaction reverses the segmentation effect. Cross-group ties emerge by design, increasing the number of bridging links across the network. At 50% domain difference, the coexistence of core-periphery structures with random and subgroup configurations across α values indicates that structural diversity is actively redistributed rather than suppressed (Pidiha, 2021). This produces a network that remains globally connected even when local clusters intensify. The operational implication is clear: deliberate introduction of heterogeneous interactions can prevent isolation of functional units. These structural regimes translate into distinct resource management modes. The systematization of approaches is presented below (Table 1).

Table 1. Structural configurations of construction crew networks and their operational implications (compiled by the author based on Jennings and Greenberg, 2009; Collie et al., 2012)

Network Structure Type	Internal Communication Logic	Coordination Pattern	Resource Flow Characteristics	Management Interpretation
Core–periphery	Centralized routing through core	Hierarchical coordination	Directed and accelerated	Efficient under stable load
Reinforced core	Multiple central hubs	Semi-distributed coordination	Parallelized with synchronization need	Flexible but coordination-sensitive

Subgroup structure	Cluster-based interaction	Decentralized coordination	Localized and segmented	Requires cross-group synchronization
Bridged clusters	Mixed local and global ties	Hybrid coordination	Balanced distribution	Optimal for adaptive environments
Random network	Unstructured connections	Unstable coordination	Unpredictable flows	Operationally inefficient

Centralized configurations prioritize speed but reduce redundancy (Lin and Wu, 2021). Clustered configurations increase robustness but introduce coordination overhead. Fragmented configurations require external synchronization mechanisms. Random configurations lack predictability and should be avoided in controlled project environments. Efficiency is not associated with a single optimal structure. It depends on maintaining the network within a bounded region where centralization, clustering, and heterogeneity coexist without dominance.

Quantitative evidence from broader agent-based studies supports this interpretation. Simulation-driven allocation strategies demonstrate measurable improvements in project performance, including delay reductions of up to 15% when interaction rules enhance coordination between agents (Mazzetto, 2024). The mechanism mirrors the observed transitions: efficiency improves when communication structures preserve connectivity while allowing adaptive redistribution of ties.

The same structural sensitivity appears in models where social networks are digitally replicated to analyze information propagation. Systems that retain heterogeneity in agent behavior produce more accurate and stable outcomes under dynamic conditions (Puri et al., 2024). Homogeneous interaction patterns, by contrast, reduce adaptability despite maintaining cohesion. Construction crews exhibit the same constraint: stability without adaptability leads to inefficiency under changing workloads.

Agent-based representations of mobility and interaction systems show that dense clusters accelerate local exchanges while bridging ties determine system-wide propagation speed (Divasson-J. et al., 2025; Pathania et al., 2025). In construction settings, these mechanisms define how quickly resources, instructions, and adjustments spread across crews. Local optimization without bridging reduces global responsiveness. Bridging without clustering reduces efficiency of execution.

Modular modeling approaches further demonstrate that interaction rules can be standardized and reused across systems without losing behavioral fidelity (Filatova et al., 2025). This indicates that the observed structural patterns are not project-specific anomalies but reproducible configurations governed by interaction logic. Sensitivity analyses confirm that small variations in parameters such as α produce disproportionate structural changes, particularly in heterogeneous populations (Bischoff and Padilla-Iglesias, 2023). This explains why minor adjustments in crew interaction policies can lead to significant differences in coordination outcomes.

The integration of adaptive agents, including those informed by language-based or data-driven decision processes, introduces the possibility of dynamic reconfiguration of interaction preferences during project execution (Gao et al., 2024). In such systems, the network does not evolve passively. It responds to operational signals. This shifts the interpretation of the model from descriptive to prescriptive: network structure becomes a controllable parameter.

Under these conditions, the evolution of construction crew networks functions as an operational indicator rather than a passive observation. Structural transitions signal changes in coordination capacity before performance degradation becomes visible. Core expansion indicates overload risk. Subgroup isolation indicates synchronization failure. Randomization indicates loss of control. Resource management efficiency emerges at the boundary between these states. The systematization of approaches is presented below (Figure 1).

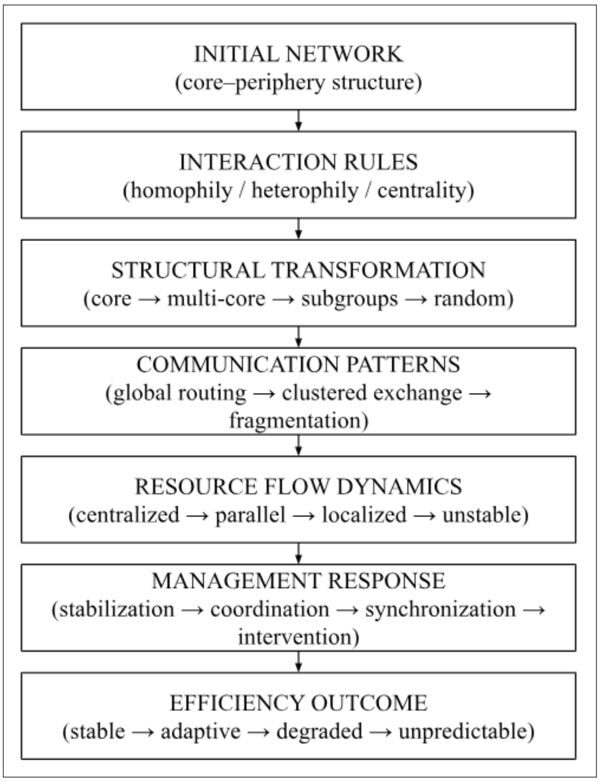

Figure 1. Mechanism of network evolution and its influence on resource management efficiency (compiled by the author based on Jennings and Greenberg, 2009; Collie et al., 2012)

It is maintained not by fixing the structure, but by regulating its evolution. The scheme clarifies that efficiency does not emerge from a stable configuration but from controlled transitions between configurations. Each structural state performs a specific coordination function. Continuity between them sustains system performance. Disruptions occur when transitions become either constrained or uncontrolled.

DISCUSSION

Communication networks inside construction crews exhibit a behavior that becomes more interpretable when viewed not as static relational maps but as evolving coordination infrastructures. Structural transformations observed across simulation regimes suggest that the network does not merely reflect collaboration patterns; it actively regulates how tasks, decisions, and resources circulate. Dense cores concentrate information flows and shorten coordination paths. Peripheral nodes rely on mediated access. This arrangement stabilizes execution in early project stages. It works because communication load remains within the absorptive capacity of central actors. Once that capacity is approached, the same structure begins to distort the distribution of operational signals. Bottlenecks form. Information does not stop moving. It accumulates.

The emergence of subgroup configurations introduces a different internal logic. Communication no longer relies on a single dominant pathway but reorganizes into multiple localized circuits. Each subgroup develops internal density and operational autonomy. Information travels faster within clusters but requires bridging ties to reach the broader system. The mechanism underlying this transformation is not fragmentation in a negative sense. It is differentiation. Under conditions where agents preferentially interact based on similarity, coordination reorganizes around shared attributes such as expertise or role proximity. Resource allocation follows these boundaries. Tasks become locally optimized. System-wide coherence depends on the persistence of inter-group connectors. When such connectors weaken, synchronization delays appear. They do not originate from lack of communication. They originate from its segmentation. Interaction preferences play a decisive role in shaping this segmentation. The systematization of approaches is presented below (Table 2).

Table 2. Interaction mechanisms and their structural effects on construction crew networks (compiled by the author based on Jennings and Greenberg, 2009; Collie et al., 2012)

Interaction Mechanism	Direction of Tie Formation	Structural Effect on Network	Impact on Connectivity	Operational Consequence
Homophily	Toward similar agents	Cluster formation	Reduced cross-group links	Local optimization increases
Heterophily	Toward dissimilar agents	Bridge creation	Increased global connectivity	Coordination flexibility improves
Degree-based attachment	Toward highly connected nodes	Gradual centralization	Moderate concentration	Stable coordination under load
Eigenvector-based attachment	Toward influential nodes	Rapid hierarchical consolidation	Strong concentration	Bottleneck risk increases
Mixed interaction regime	Combined directional preferences	Hybrid network structures	Balanced connectivity	Adaptive coordination becomes possible

Homophily-driven attachment produces structurally coherent but increasingly partitioned systems. Heterophily-driven attachment redistributes ties across dissimilar nodes, preserving connectivity at the expense of local cohesion. Neither mechanism alone yields stable performance across all project phases. Their interaction defines the operational envelope of the system. At early stages, homophily reinforces predictable communication channels. At later stages, excessive homophily reduces adaptability. Heterophily compensates by reintroducing cross-functional links. The network does not choose between them. It oscillates depending on task requirements and environmental constraints.

The introduction of centrality-based selection modifies how influence propagates across the network. Degree-based attachment distributes influence proportionally to connection count. Eigenvector-based attachment amplifies the effect of connections to already influential nodes. The difference appears subtle at the level of individual ties. It becomes structural at scale. Under eigenvector-driven dynamics, coordination centers consolidate earlier. Decision pathways shorten but become more dependent on a smaller subset of actors. This accelerates response time under stable conditions. It increases vulnerability under disruption. Influence does not distribute evenly. It cascades.

Previous research on agent-based systems provides a consistent explanation for this sensitivity to interaction rules. Micro-level decision patterns generate macro-level structures that cannot be inferred from aggregated models. Systems composed of heterogeneous agents exhibit emergent behaviors precisely because local interactions are not uniform. Construction environments share this property with other complex systems such as urban mobility networks and supply chains, where local decisions reshape global dynamics through repeated interactions. Simulation studies in these domains show that small adjustments in interaction parameters lead to non-linear structural effects. The present analysis aligns with this observation. Slight variations in similarity preference or connectivity bias produce disproportionate changes in network topology. The system is parameter-sensitive.

At the same time, the interpretation of network evolution as an operational indicator extends beyond earlier applications of social network analysis in construction research. Traditional approaches often treated network structures as descriptive artifacts, capturing communication patterns at specific time points. Longitudinal and simulation-based approaches introduce a different perspective. They treat structure as a process. The network is not measured. It is generated. This shift allows the detection of transitional states that precede observable performance issues. Core expansion signals increasing coordination load. Subgroup isolation signals emerging misalignment. Randomization signals loss of structural control. These signals appear before delays or inefficiencies become measurable at the project level.

The integration of these findings with broader research on agent-based modeling clarifies why such predictive capacity emerges. Agent-based frameworks capture the recursive relationship between individual behavior and system configuration. Each agent processes local information and forms connections based on internal rules. The resulting structure feeds back into subsequent decisions by altering available communication paths. This feedback loop creates path dependency. Once a structural pattern emerges, it influences future interactions. The system evolves through its own history. Construction crews exhibit this property in practice. Established communication channels persist even when conditions change. Adaptation requires structural reconfiguration, not only behavioral adjustment.

Operational implications follow from this recursive mechanism. Resource management cannot rely solely on optimizing task assignments or scheduling sequences. It must consider the structure through which these assignments propagate. A highly centralized network accelerates initial coordination but limits scalability. A highly clustered network supports parallel execution but requires synchronization layers. A poorly connected network increases uncertainty. The challenge lies in maintaining structural balance rather than selecting a single configuration. Networks that remain within a bounded region of connectivity and differentiation sustain both efficiency and adaptability. Outside this region, performance degrades in predictable ways.

Several limitations should be acknowledged. The analysis relies on simulated interaction processes calibrated through empirical configurations but does not incorporate continuous real-time data from active construction projects. Behavioral rules assigned to agents simplify decision-making processes and do not fully capture cognitive or organizational factors influencing communication. Differences in methodological design across related studies restrict direct comparison, particularly where alternative modeling paradigms such as system dynamics or discrete-event simulation aggregate interactions differently. Network size and composition are constrained to representative scenarios rather than exhaustive variations. Environmental variables such as contractual structures, cultural factors, and technological infrastructure remain outside the modeled system. These factors influence real-world communication but are not explicitly encoded in the simulation.

Another limitation concerns temporal resolution. Network evolution is observed through discrete simulation steps, while actual construction processes involve overlapping and asynchronous interactions. The model captures structural tendencies but not the exact timing of transitions. In practice, delays or disruptions may emerge from temporal misalignment rather than structural configuration alone. The absence of real-time feedback mechanisms further constrains the ability to simulate adaptive management interventions. The system evolves according to predefined rules. It does not incorporate external corrective actions dynamically.

Despite these constraints, the analytical perspective introduced here modifies how construction crew coordination can be interpreted. Network structures do not simply support project execution. They shape it. Changes in connectivity alter how information is transmitted, how decisions are processed, and how resources are redistributed across operational layers. Monitoring these structures provides early signals of emerging inefficiencies. Adjusting interaction patterns influences outcomes before delays materialize.

CONCLUSION

Structural transformations observed in construction crew networks reveal that coordination systems operate through continuously changing interaction patterns rather than through fixed organizational forms. Centralized configurations provide stability under limited load, while clustered and distributed structures introduce flexibility but require synchronization. These patterns do not replace one another. They coexist and transform.

The first objective was addressed through identification of recurring structural configurations and their dependence on interaction rules. The second objective was resolved by explaining how these configurations reshape communication pathways and redistribute resource flows. The third objective was fulfilled by modeling the conditions under which transitions between structures influence coordination efficiency.

The hypothesis is supported. Efficiency does not emerge from structural stability. It depends on controlled variability.

Network evolution does not act as a background process. It defines the conditions under which coordination occurs.

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