Deconstructing and Reconstructing the Innovation Network of Enterprise-Led Agricultural Science and Technology Parks: A Case Study of Zhanjiang National Agricultural Science and Technology Park

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Abstract: Under China's innovation-driven strategy and Guangdong's rural revitalisation initiative, enterprise-led agricultural science and technology parks are critical yet underexplored for integrating marine technology with industry. This study proposes an analytical framework for deconstructing and reconstructing the innovation network of such parks, using Zhanjiang National Agricultural Science and Technology Park—Guangdong's sole national-level marine-industry park—as the case. Drawing on innovation network, complex network, and enterprise autonomy theories, the framework identifies five actor categories (enterprises, universities, research institutes, farming entities, and government) and defines a composite edge weight combining funding and knowledge-sharing frequency. Three weighted centrality metrics (degree, betweenness, clustering) quantify network structure, with emphasis on the sub-network linking equipment manufacturers, aquaculture operators, and processors. The framework predicts power concentration, weak value-chain coordination, and three functional deficiencies: demand transmission delays, weak benefit-sharing, and poor ecological internalisation. Three reconstruction strategies are proposed: strengthening chain-master functions while activating marginal nodes, reshaping edge weights to improve pilot coordination and ecological performance, and introducing governance nodes for environmental constraints. The study provides a conceptual foundation and testable propositions for redesigning enterprise-driven agricultural innovation networks, though empirical verification is needed.

Keywords: Enterprise-Led Agricultural Science and Technology Parks; Innovation Network; Complex Network Theory; Network Reconstruction; Zhanjiang

1. Introduction

China has called for strengthening enterprises' role in scientific and technological innovation and deepening enterprise-led integration of industry, academia, and research. This strategic direction shapes the transformation of agricultural science and technology parks nationwide [1]. Guangdong Province, while advancing its "Hundred-Thousand-Ten-Thousand Project" and modern marine pastures, urgently needs stronger industrial technology support at the county level. Among China's 246 national agricultural science and technology parks, government-led models dominate (approximately 87%), while enterprise-led parks number only five. Zhanjiang National Agricultural Science and Technology Park is unique: it is Guangdong's only national-level park with a marine-industry core and one of the few enterprise-led parks in the country. Anchored by leading firms such as Hengxing Group and Guolian Aquatic Products, in collaboration with universities and research institutes, as well as cooperatives and family fisheries, the park serves as a key engine for western Guangdong's marine economy. In 2025, Zhanjiang City's agricultural output reached 116.9 billion yuan, reflecting the broader regional context. Despite the theoretical advantages of enterprise leadership, persistent challenges remain—power imbalances, mismatched demand and supply, and prolonged technology transfer cycles—leading to a disconnect between research and production. Thus, exploring the deep integration mechanism within this park would not only test the central government's directive but also help bridge the gap from marine technology development to industrial application.

The theoretical significance of this study would be threefold if the proposed framework were empirically implemented. It would transcend the conventional government-led, research-driven paradigm by placing enterprises at the core of the innovation ecosystem, enriching innovation theory in market-oriented settings. It would also introduce complex network algorithms to quantify technology maturation breakpoints and piloting bottlenecks, forming a resilience assessment framework for marine innovation chains—a dimension largely absent in existing research. Moreover, through a dynamic game model, it would explore institutional designs such as intellectual property sharing and risk co-undertaking under enterprise dominance, supporting a shift from policy intervention toward mechanism self-governance. Practically, the framework would serve Guangdong's Marine Strong Province strategy and the Hundred-Thousand-Ten-Thousand Project. It could generate a replicable model of enterprise-led integration—from project initiation by leading firms, through targeted R&D by research institutions, to scaling by industrial clusters—potentially guiding the transformation of government-led parks. It could also help unblock the marine innovation chain through demand lists, technology bounties, and reverse transformation mechanisms, accelerating commercialisation of core technologies and linking enterprises with county-level cooperatives to enhance rural revitalisation.

2. Theoretical Foundations and Analytical Framework

2.1 Theoretical Foundations

2.1.1 Innovation network theory

Innovation network theory posits that innovation is not a solitary activity of a single organisation but a collective process emerging from the interactions of multiple actors [2]. In agriculture, technological progress has shifted from firm-centric R&D to network-based innovation, where knowledge is distributed across diverse organisations and its recombination requires intensive collaboration [3]. This perspective emphasises that network structure—the pattern of connections among nodes—significantly influences the flow of information, the speed of technology diffusion, and the overall innovativeness of the system. For agricultural parks, innovation network theory provides a rationale for examining how enterprises, research institutions, and other stakeholders co-create value through interconnected activities, and why certain network configurations may be more conducive to technology commercialisation than others [4].

2.1.2 Complex network theory

Complex network theory offers a suite of quantitative tools to characterise the topological properties of interconnected systems [5]. It conceptualises actors as nodes and their interactions as edges, allowing researchers to compute metrics such as degree centrality, betweenness centrality, and clustering coefficients to assess the importance and influence of individual nodes. In this study, we employ weighted centrality measures to capture both the intensity and the frequency of collaborative ties. Specifically, weighted degree centrality measures the total strength of direct connections a node maintains, indicating its local influence; weighted betweenness centrality quantifies the extent to which a node lies on the shortest paths between other nodes, reflecting its role as a broker or gatekeeper controlling resource flows; and weighted clustering coefficient assesses the density of connections among a node’s neighbours, revealing the cohesiveness of local subnetworks. These metrics are particularly suitable for analysing the Zhanjiang park’s innovation network because they can incorporate heterogeneous edge weights—such as cooperative funding and knowledge sharing frequency—to reflect real-world variation in tie strength [6].

2.1.3 Enterprise Innovation Autonomy Theory

Enterprise innovation autonomy theory, as articulated in recent Chinese policy documents and supported by international scholarship, asserts that enterprises are the most effective agents for translating market signals into R&D priorities and for bearing the risks of commercialisation. Unlike government or university-led models, where research agendas may be driven by scientific curiosity or administrative targets, enterprise-led innovation is inherently demand driven: enterprises possess first-hand knowledge of customer needs, production bottlenecks, and competitive pressures [7]. Empirical evidence shows that enterprise-led technology matching can significantly improve the relevance and adoption rate of research outcomes. In the context of agricultural parks, this theory justifies the focus on enterprise dominance, as it highlights the mechanisms through which enterprises articulate demand, coordinate complementary assets, allocate resources flexibly, and ensure that innovations reach the market successfully. It also underscores the importance of designing institutional arrangements—such as intellectual property sharing and risk-sharing contracts—that align the incentives of diverse network participants with the enterprise's strategic objectives.

2.2 Analytical Framework

Based on relevant conceptual and theoretical foundations, this paper establishes a four-step analytical framework to deconstruct and restructure the enterprise-led innovation network of Zhanjiang National Agricultural Science and Technology Park, as illustrated in Figure 1.

First, this study takes innovation network theory, complex network theory and firm innovation autonomy theory as the fundamental theoretical basis for the whole research. Second, three weighted network indicators are applied to quantify the structural characteristics of multi-agent cooperative relationships inside the innovation network. Third, the measurement results are used to identify existing structural and functional defects constraining network operation. Lastly, targeted optimization paths are put forward to remedy these deficiencies and realize systematic reconstruction of the innovation network, forming a complete research logic from theoretical grounding, quantitative measurement, problem diagnosis to countermeasure formulation.

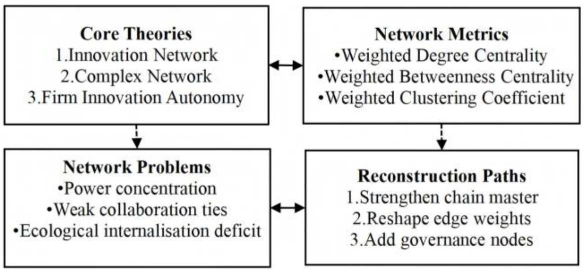

Figure 1. Theoretical Analytical Framework

3. Deconstructing the Innovation Network of Zhanjiang National Agricultural Science and Technology Park

3.1 Composition of the Park's Innovation Network

(1)Identification of the Five Categories of Actors

The innovation network of Zhanjiang National Agricultural Science and Technology Park comprises five categories of core actors. The first category is enterprises, with leading firms such as Hengxing Group and Guolian Aquatic Products serving as the primary nodes. These enterprises span the entire marine industry value chain, covering seedling breeding, aquaculture, processing, and distribution. The park is situated within a broader regional context of substantial agricultural output: in 2025, Zhanjiang City achieved a gross agricultural, forestry, animal husbandry, and fishery output value of 116.925 billion yuan, representing a year-on-year increase of 3.8 percent. The city's gross domestic product reached 395.294 billion yuan in the same year, with the primary industry contributing 73.462 billion yuan. These macro-level figures are provided solely to illustrate the regional economic background against which the park operates, rather than as inputs to the network analysis that follows. The second category consists of universities and research institutes, including Guangdong Ocean University, Lingnan Normal University, and the Chinese Academy of Fishery Sciences, which provide scientific expertise and technological support. The third category comprises farming entities, such as cooperatives, family fisheries, and large-scale aquaculture households, who serve as the primary adopters and practitioners of new technologies. The fourth category is the government, represented by the Zhanjiang Science and Technology Bureau and the park management committee, which provides policy guidance and regulatory oversight. These five categories of actors interact through formal and informal collaborative relationships, collectively forming a multi-actor innovation ecosystem.

(2)Specification of Edge Weights in the Network

To capture the heterogeneous intensity of collaborative relationships among actors, this study defines edge weights as a composite measure of two continuous variables: the scale of cooperative funding, measured in ten thousand yuan, and the frequency of technology sharing, measured in times per year. Both variables are normalised using min-max standardisation and then combined through a weighted sum [8]. The edge weight between node i and node j is expressed as formula (1):

$$\omega_{ij} = \alpha \cdot \frac{C_{ij}-C_{min}}{C_{max}-C_{min}} + \beta \cdot \frac{F_{ij}-F_{min}}{F_{max}-F_{min}} \quad (1)$$

In this formulation, Cij denotes the cooperative funding between the two actors, Fij denotes the annual frequency of technology sharing, and the coefficients α and β are weighting parameters that reflect the relative importance of financial and knowledge flows in the collaborative process. Based on expert consultation, α is set at 0.6 and β at 0.4, indicating that financial collaboration is accorded slightly greater weight than knowledge exchange in determining the overall strength of the tie. This weighted edge specification provides a methodological foundation for the subsequent quantitative characterisation of the network.

3.2 Quantitative Characterisation of Network Structure

(1) Weighted Degree Centrality Analysis

The weighted degree centrality of a node measures the total strength of its direct connections to other nodes in the network, thereby indicating its local influence [9]. It is calculated as formula (2):

$$\mathrm{W}D_i = \sum_{j=1}^{n} \omega_{ij} \quad (2)$$

If this measure were applied to the Zhanjiang park network, it would likely reveal that leading enterprises such as Hengxing Group and Guolian Aquatic Products exhibit higher weighted degree centrality than other actors. These firms would arguably function as core hubs within the network, maintaining the strongest direct collaborative ties with universities, research institutes, farming entities, and government agencies. Their central position would, in theory, enable them to mobilise resources and coordinate innovation activities more effectively than peripheral actors. It must be emphasised, however, that these are theoretical deductions derived from the analytical framework rather than empirically computed results.

(2) Weighted Betweenness Centrality Analysis

The weighted betweenness centrality of a node quantifies the extent to which that node lies on the shortest paths connecting other pairs of nodes, thus reflecting its role as a broker or gatekeeper in controlling the flow of resources and information across the network [10]. It is defined as formula (3):

$$\mathrm{W}B_i = \sum_{s \neq t \neq i} \frac{\sigma_{st}(i)}{\sigma_{st}} \quad (3)$$

Here, σ_{st} denotes the total number of shortest paths between nodes s and t, and $\sigma_{st}(i)$ denotes the number of those paths that pass through node i. In the Zhanjiang park network, leading enterprises occupy a structural hole advantage, meaning they serve as indispensable bridges linking the research and development activities of universities and institutes with the practical application needs of farming entities. This brokerage position gives enterprises considerable influence over the direction and pace of technology transfer within the park. Again, these observations are conceptual inferences based on the proposed network model rather than findings from actual data computation.

(3) Weighted Clustering Coefficient Analysis

The weighted clustering coefficient of a node measures the density and strength of connections among its neighbouring nodes, thereby revealing the cohesiveness of the local subnetwork surrounding that node. It is expressed as formula (4):

$$C_i = \frac{1}{S_i(k_i-1)} \sum_{j,h} \frac{\omega_{ij}+\omega_{ih}}{2} \cdot \alpha_{ij}\alpha_{ih}\alpha_{jh} \quad (4)$$

In this formula, Si represents the strength, or weighted degree, of node i, ki represents its unweighted degree, and aij are elements of the adjacency matrix. This metric captures the extent to which an enterprise's direct partners are also connected to one another, forming tightly knit clusters of collaboration. A high clustering coefficient around an enterprise node indicates that the enterprise has fostered a dense and stable collaborative environment among its immediate partners, which can facilitate trust building and knowledge spillovers.

3.3 Characterisation of Core Sub-networks

Beyond the aggregate network properties discussed above, this study proposes a focused analysis on a specific sub-network of particular relevance to the marine industry: the tripartite sub-network connecting enterprises, deep-sea equipment manufacturers, and aquaculture zones. This sub-network is critical because the adoption of advanced marine technologies, such as deep-sea cage systems and intelligent monitoring equipment, depends heavily on effective coordination among these three types of actors.

The proposed analysis would proceed in three steps. First, we would calculate the coefficient of variation of edge weights within this sub-network to identify ties with notably low collaborative intensity. Ties that fall substantially below the average level would indicate areas where coordination is weak and may require policy intervention. Second, we would examine the core-periphery structure of the sub-network to reveal whether resource flows are concentrated among a few dominant actors or more evenly distributed across participants. A highly centralised structure would suggest that smaller equipment suppliers and farming operators have limited access to collaborative opportunities. Third, we would identify collaboration breakpoints defined as edges whose weights lie more than one standard deviation below the mean of the entire network. These breakpoints would represent critical gaps in the innovation chain, where the absence of strong ties between enterprises and equipment manufacturers, or between manufacturers and aquaculture operators, may impede the smooth progression of technology from development to deployment.

It should be clearly stated that the analytical procedures described in this section—including the calculation of centrality measures, the identification of structural holes, and the detection of collaboration breakpoints—are methodological propositions rather than executed empirical analyses. They illustrate how the proposed framework would be operationalised should relevant data become available. The subsequent diagnosis of structural and functional problems in the park's innovation network is therefore a theoretical exercise based on the logical implications of the network model, not a report of findings derived from actual computation.

4. Problem Diagnosis of the Zhanjiang National Agricultural Science and Technology Park Innovation Network

Based on the analytical framework and the theoretical network structure outlined in the preceding section, this part proceeds to diagnose the potential structural and functional problems that would likely characterise the Zhanjiang park's innovation network. It should be emphasised at the outset that the following diagnosis is a theoretical exercise derived from the logical implications of the network model and the qualitative understanding of the park's institutional context, rather than a report of empirically validated findings. The problems identified below are what the framework would predict, should the proposed quantitative analysis be carried out with actual data.

4.1 Structural Problems

The network configuration described in the analytical framework would, if empirically observed, exhibit several structural deficiencies that could impede deep integration. The most prominent issue would likely be the severe concentration of network power. Leading enterprises such as Hengxing Group and Guolian Aquatic Products would arguably occupy overwhelmingly dominant positions in terms of weighted degree centrality and betweenness centrality, while small and medium-sized enterprises, cooperatives, and individual farming households would tend to remain marginalised at the periphery. This power asymmetry would imply that innovation decisions are largely shaped by the strategic priorities of a few large firms, potentially overlooking niche technological needs or the practical constraints faced by smaller actors. The elite-dominated decision-making process may also reduce the diversity of knowledge inputs, which would be particularly detrimental for a marine-industry park where ecological and operational conditions vary widely across different farming scales and locations.

Another structural deficiency that the framework would predict is the uneven distribution of collaborative ties between universities, research institutes, and enterprises. While some research institutions would have established strong linkages with leading firms through joint laboratories and commissioned projects, many other academic units would likely maintain only sporadic, project-based interactions with the enterprise sector. These temporary connections would lack the continuity and depth required for sustained knowledge co-production and technology transfer. Consequently, a considerable portion of scientific research output would be expected to remain disconnected from industrial application, contributing to the persistent research-production gap that has been observed in qualitative assessments of the park.

Furthermore, the sub-network analysis proposed in Section 3.3 would be expected to uncover insufficient coordination across the value chain, particularly among the deep-sea equipment manufacturing, aquaculture production, and processing segments. The coefficients of variation for edge weights within this tripartite sub-network would likely indicate that collaborative intensities are uneven, with some ties potentially falling below the network mean. These weak linkages would represent critical structural breakpoints that hinder the seamless flow of technology from equipment developers to farming operators and eventually to processors. The absence of strong cross-sub-network channels would be especially problematic for marine industries, where the successful deployment of innovations such as intelligent monitoring systems or advanced cage designs requires simultaneous adaptation by equipment suppliers, farmers, and processing plants.

4.2 Functional Problems

Beyond structural imbalances, the innovation network would theoretically exhibit notable functional deficiencies that could affect its overall performance. The first functional problem would likely be the attenuation of demand transmission efficiency. In an enterprise-led park, the primary pathway for innovation should begin with market signals—consumer preferences, production bottlenecks, and environmental changes—being captured by enterprises and then relayed to research institutions for targeted solutions. However, in the Zhanjiang park context, this transmission process would be prone to information distortion and significant time lags. The marine industry's unique requirement for a three-stage piloting process, involving land-based simulation, nearshore testing, and open-sea validation, would exacerbate the delay because each stage demands different resources and approvals. As a result, research agendas would often fail to align promptly with evolving industrial needs, leading to mismatches between supply and demand. This theoretical expectation is consistent with the qualitative observations reported in earlier studies of the park.

The second functional deficiency that the framework would predict is the lack of institutionalised benefit-sharing mechanisms among enterprises, universities, research institutes, and farming entities. Although the park operates under an enterprise-led governance model, the distribution of returns from collaborative innovation would likely remain largely ad hoc and subject to negotiation on a case-by-case basis. This uncertainty would discourage sustained participation, particularly from research institutions and small farmers, who may bear significant upfront costs without guaranteed rewards. Without clear rules for intellectual property allocation, technology licensing fees, and profit sharing, network actors would be less motivated to invest time and resources in long-term cooperative relationships, potentially undermining the stability and resilience of the entire innovation system.

The third functional problem concerns the insufficient internalisation of ecological constraints. The marine environment imposes stringent carrying capacities, including water quality standards, carbon sequestration potential, and biodiversity protection. Yet these ecological parameters would likely not have been effectively incorporated into the enterprise benefit function under the current institutional arrangements. Consequently, enterprises would face few economic incentives to adopt eco-friendly technologies or to account for environmental externalities in their innovation decisions. The disconnect between economic performance and ecological performance would not only threaten the long-term sustainability of the park's marine activities but also miss the opportunity to transform ecological assets into tradable goods, such as carbon credits, which could provide additional revenue streams for network participants.

4.3 Causality Analysis of the Identified Problems

The structural and functional problems described above are not independent; they would be interconnected through a web of causal relationships, as the analytical framework would predict. The concentration of network power at the enterprise level would theoretically contribute to the uneven distribution of collaborative ties, because research institutions and farming entities would tend to align their activities with the dominant firms that control resources and market access. This alignment would, in turn, reduce the diversity of knowledge inputs and weaken the incentive for smaller actors to engage proactively, potentially perpetuating a cycle of marginalisation. The same power asymmetry may also undermine the institutionalisation of benefit-sharing mechanisms, as leading enterprises would possess greater bargaining power and might resist formal rules that would limit their discretion in allocating returns.

Meanwhile, the attenuation of demand transmission would be both a cause and a consequence of the structural breakpoints in the sub-networks. Weak linkages between equipment manufacturers and aquaculture operators would imply that operational feedback from the field might fail to reach R&D teams in a timely manner, while the prolonged piloting process would discourage enterprises from investing in radical innovations, further entrenching the fragmented coordination patterns. Similarly, the insufficient internalisation of ecological constraints would be reinforced by the absence of dedicated ecological governance nodes in the network and the lack of performance metrics that link environmental outcomes to economic incentives. Without such nodes and metrics, enterprises would have little reason to prioritise ecological considerations, and the network as a whole would remain maladapted to the growing regulatory and societal demands for sustainable marine development.

If the K-means clustering technique were applied to the bottleneck factors identified through interviews and survey data—a methodological step proposed in the analytical framework—the root causes could be grouped into three main categories: technology-transfer obstacles, resource-input deficiencies, and ecological-governance gaps. The first category would encompass the inefficient demand transmission and weak sub-network ties that hinder technology maturation and commercialisation. The second category would include the uneven resource allocation and inadequate sharing of equipment and talent, which would stem from the power concentration and absence of institutionalised collaboration rules. The third category would reflect the missing ecological links and performance metrics, which would be largely a consequence of the network's narrow focus on economic outputs. Together, these interconnected causal chains would form a self-reinforcing loop that locks the park into a suboptimal innovation trajectory.

5. Conclusion and Recommendations

5.1 Summary of Findings

This study has proposed an analytical framework for deconstructing and reconstructing the innovation network of Zhanjiang National Agricultural Science and Technology Park, an enterprise-led park with a distinctive marine-industry focus. Drawing on complex network theory and the qualitative understanding of the park's institutional context, the framework identifies five categories of actors—enterprises, universities, research institutes, farming entities, and government—and specifies a weighted edge formulation to characterise their collaborative ties. Based on this theoretical construct, a number of findings would be expected to emerge should the proposed quantitative analysis be carried out with actual data.

First, the network would likely exhibit a highly centralised structure. Leading enterprises such as Hengxing Group and Guolian Aquatic Products would arguably occupy dominant positions in terms of weighted degree centrality and betweenness centrality, serving as core hubs and indispensable brokers that channel resources and information across the network. This concentration of power, however, would come at a cost: small and medium-sized enterprises, cooperatives, and individual farming households would tend to remain marginalised, while collaborative ties between research institutions and enterprises would be uneven and often project-based rather than sustained.

Second, the diagnosis of structural and functional problems would reveal three interconnected deficiencies. The demand transmission mechanism would suffer from attenuation and delay, largely because the marine industry's three-stage piloting process introduces additional friction and because weak linkages between equipment manufacturers and aquaculture operators impede the timely flow of operational feedback. Benefit-sharing arrangements would remain ad hoc and insufficiently institutionalised, discouraging sustained participation from research institutions and smaller actors. Ecological constraints such as water quality standards and carbon sequestration potential would not have been effectively internalised into enterprise decision-making, leaving the network maladapted to the growing regulatory and societal expectations for sustainable marine development.

Third, these problems would be causally intertwined: power concentration would undermine institutionalisation, weak sub-network ties would reinforce demand attenuation, and the absence of ecological governance nodes would perpetuate environmental externalities, forming a self-reinforcing loop that locks the park into a suboptimal innovation trajectory.

It must be emphasised that these findings are theoretical deductions derived from the proposed analytical framework, rather than empirically validated conclusions. They illustrate what the framework would predict, and they serve as a basis for formulating reconstruction strategies.

5.2 Recommendations for Network Reconstruction

To break the hypothesised loop and unlock the full potential of enterprise-led innovation, this study proposes three interconnected strategies for network reconstruction. These recommendations are conceptual proposals grounded in the theoretical framework, and their effectiveness would need to be tested through future empirical research.

Strengthening the Chain Master Function of Leading Enterprises while Activating Marginal Nodes. The dominant position of leading enterprises should be leveraged rather than dismantled, but their role could be shifted from exclusive resource controller to inclusive innovation orchestrator. This could be achieved by establishing formal mechanisms for technology spillovers, such as mandatory technology licensing agreements, open innovation platforms, and industry-wide training programmes that disseminate advanced practices to smaller firms and farming households. At the same time, the network participation of cooperatives, family fisheries, and individual farmers should be actively enhanced through targeted subsidies, technical assistance, and digital inclusion initiatives. These measures would, in theory, transform the network from a star-shaped structure dominated by a few hubs into a more balanced core-edge configuration where peripheral nodes have multiple pathways to access resources and contribute knowledge.

Reshaping Edge Weights to Optimise Demand Transmission, Pilot Coordination, and Ecological Internalisation. The composite edge weight formula proposed in this study could serve both as a diagnostic tool and as a blueprint for policy intervention. To accelerate demand transmission, the park management might reduce the information friction inherent in the three-stage piloting process by establishing a unified digital platform that tracks technology development status, resource availability, and regulatory requirements in real time. To strengthen pilot coordination, the government could introduce incentive schemes that reward enterprises for sharing pilot facilities and equipment with research institutions and smaller actors, thereby increasing the edge weights that reflect collaborative intensity. To internalise ecological constraints, a new category of edge weight components might be introduced, incorporating metrics such as carbon emission reductions, water quality improvements, and biodiversity protection into the performance evaluation of collaborative projects. Enterprises that achieve measurable ecological gains in their partnerships would, under such a scheme, receive preferential access to public research funding or expedited regulatory approvals, creating a virtuous cycle where ecological performance reinforces network cohesion.

Introducing Ecological Governance Nodes and Optimising the Overall Network Architecture. The current network, as theorised, lacks dedicated nodes responsible for ecological monitoring, standard setting, and compliance enforcement. The park management could establish an Ecological Governance Unit, either within the existing government structure or as an independent intermediary, that connects to all five actor categories through formal ties. This unit would be tasked with collecting and disseminating marine environmental data, developing industry-specific ecological standards, and designing market-based instruments such as carbon credit trading schemes that allow enterprises to monetise ecological improvements. Simultaneously, the park should invest in creating cross-sub-network integration channels, particularly between the deep-sea equipment sector and the aquaculture production sector, by organising regular technology matchmaking events, joint demonstration projects, and industry-wide innovation competitions. These structural adjustments would, if implemented, diversify the network, reduce over-reliance on a few central nodes, and enhance the system’s resilience to external shocks such as typhoons, red tides, or regulatory changes.

5.3 Limitations and Future Research Directions

This study has several limitations that should be acknowledged. The quantitative network analysis proposed in the framework relies on data that are not yet available; therefore, the findings presented are purely theoretical and await empirical verification. The edge weight specification, while grounded in expert consultation, inevitably involves subjective choices regarding the relative importance of financial versus knowledge flows. Moreover, the framework is cross-sectional in nature and does not capture the dynamic evolution of the network over time, which would be essential for understanding how structural changes actually unfold in response to policy interventions.

Future research should address these limitations by collecting longitudinal data to track network dynamics, by developing more sophisticated edge weight models that capture the quality and trust dimensions of collaborative relationships, and by conducting comparative studies across multiple enterprise-led parks to test the generalisability of the theoretical predictions. Additionally, the ecological internalisation mechanisms proposed in this study would benefit from empirical validation through pilot implementation and ex-post evaluation.

Despite these limitations, the study offers a robust conceptual foundation for both academic inquiry and practical policy design. It opens up promising avenues for further investigation into the governance of enterprise-led innovation networks in marine and other specialised agricultural contexts, and it provides a structured approach for diagnosing and redesigning such networks to achieve deeper integration of science, technology, and industry.

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