ISSN: 2688-8645

A System Dynamics Approach to Optimizing Pension Insurance Pooling Governance: A Four-Dimensional Collaborative Path for Yingkou City

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Abstract

Based on the author's doctoral dissertation, this paper examines how system dynamics can be used to optimize regional pooling governance in China's pension insurance system under unified provincial pooling rules. Using Yingkou City in Liaoning Province as the focal case and drawing on comparative evidence from the province's 13 prefecture-level cities during 2015-2024, the paper integrates three layers of evidence: efficiency decomposition, influencing-factor identification, and dynamic pathway simulation. The preceding dissertation results show that Yingkou's main efficiency bottleneck lies in pure technical efficiency (PTE) rather than scale efficiency (SE): the mean PTE is 0.60, clearly lower than the mean SE of 0.89, and during the 2020 shock year PTE declined to 0.54 while SE remained relatively stable at 0.88. This structure indicates that fragmented procedures, inconsistent information standards, weak interdepartmental coordination, and incomplete closed-loop supervision are more important obstacles than simple scale shortage. On this basis, a system dynamics framework is constructed with stock variables such as cumulative fund balance, insured population, benefit recipients, and governance-capacity stock; flow variables such as contribution revenue, fiscal subsidies, benefit expenditure, and risk handling; and four policy dimensions of policy adaptation, resource integration, technological empowerment, and regulatory assurance. The analysis shows that isolated digitalization is insufficient for sustained governance improvement. More stable gains require coordinated reform that first clarifies rules and closes high-frequency processes, then improves resource coordination and data connectivity, and finally embeds risk control and performance constraints into routine operations. The paper therefore proposes a phased optimization path for Yingkou that centers on benefit-eligibility certification, automatic cross-department verification, process reengineering, and continuous monitoring of process-performance indicators. The study contributes a practical city-level pathway for pension insurance governance and extends the dynamic-balance view of efficiency from measurement to simulation-based policy design.

Keywords

Pension Insurance; System Dynamics; Regional Pooling Efficiency; Yingkou City; Digital Governance; Four-Dimensional Collaborative Mechanism.

1. Introduction

1.1. Research Background and Problem Orientation

With the continued advancement of national pooling and the convergence of provincial pooling rules in China's basic pension insurance system, the key governance challenge is no longer simply whether the pooling level should be raised, but how city-level pooling units can convert unified institutional rules into high-quality operational performance. Under the same provincial framework, differences remain in population ageing, industrial structure, fiscal

ISSN: 2688-8645

space, digital foundations, and administrative coordination. These differences shape whether pension insurance governance can achieve a workable balance among cost control, benefit protection, and long-term sustainability. In this context, Yingkou City represents a typical transformation-oriented city in Northeast China where industrial restructuring, demographic pressure, and governance modernization overlap. [1-2]

Existing research has provided extensive discussions on national pooling, provincial adjustment, fund sustainability, and institutional equity, yet three gaps remain. First, many studies stop at the measurement of efficiency and do not move far enough toward mechanism explanation and pathway design. Second, digital governance is often discussed as a general background rather than as a process variable that directly affects contribution collection, eligibility certification, payment review, and risk control. Third, relatively few studies connect static efficiency evidence to a dynamic policy-combination framework capable of comparing short-, medium-, and long-term effects. This paper addresses these gaps by bringing system dynamics into the analysis of regional pooling efficiency in Yingkou.

1.2. Article Objective and Analytical Contribution

This paper does not repeat a broad comparison of pension insurance efficiency. Instead, it uses the dissertation evidence on Yingkou's efficiency structure as the entry point for a more focused question: how can a city whose main bottleneck lies in process efficiency rather than scale efficiency design a stable optimization path under unified provincial rules? To answer this question, the paper combines the dynamic-balance view of efficiency with a four-dimensional collaborative mechanism consisting of policy adaptation, resource integration, technological empowerment, and regulatory assurance.

The contribution of the paper is threefold. First, it translates the dynamic-balance view of efficiency from a measurement concept into a simulation-oriented governance framework. Second, it explains why isolated digitalization does not necessarily improve efficiency in a sustained way. Third, it proposes a staged implementation roadmap for Yingkou that is organized around process friction reduction, rather than around broad calls for additional input or large-scale institutional redesign.

1.3. Data Foundation and Research Methods

The paper is grounded in the author's doctoral dissertation on the regional pooling efficiency of China's pension insurance, using Yingkou City as the focal case and the 13 prefecture-level cities of Liaoning Province as the comparative background for 2015-2024. The evidence base comes from three linked methodological layers. First, efficiency measurement is derived from SBM-DEA under the variable-returns-to-scale setting. Second, the main influencing factors are identified through panel Tobit analysis. Third, a system dynamics model is used to organize the feedback structure of institutional, resource, technological, and regulatory variables and to compare alternative governance paths over time. [3-4]

2. Theoretical Basis and Analytical Framework

2.1. The Dynamic-balance View of Efficiency

The dynamic-balance view of efficiency holds that pension insurance governance cannot be judged by a single financial outcome such as lower expenditure or higher balances. Pension insurance is a public institutional arrangement whose performance must be evaluated simultaneously in terms of administrative and resource-use efficiency, the stability and timeliness of benefit delivery, and the sustainability of the system under ageing, mobility, and fiscal pressure. For this reason, efficiency should be understood as a governance equilibrium among cost control, protection, risk control, and long-term resilience.

ISSN: 2688-8645

This perspective is especially important for city-level studies. Under unified provincial rules, many differences in formal system design have already been compressed. What remains highly variable is how rules are translated into practice. Hence, efficiency decomposition becomes crucial. When scale efficiency is relatively high but pure technical efficiency is low, the main problem lies in process organization, coordination quality, and governance friction rather than in the lack of scale itself. [5-8]

2.2. Why System Dynamics Is Needed Beyond DEA and Tobit

DEA and Tobit play indispensable roles, but they each capture only one part of the governance picture. DEA identifies where the efficiency gap lies by separating overall efficiency, pure technical efficiency, and scale efficiency. Tobit explains which factors are statistically associated with these differences under bounded dependent variables. Yet the governance of pension insurance is deeply dynamic: standardized collection affects fund revenue stability; fund pressure influences fiscal support and administrative arrangements; digital governance changes the intensity of manual intervention; and stronger regulation alters abnormal-payment risk and back-end remediation costs. These effects unfold through feedback loops and time lags, which static models alone cannot fully display.

System dynamics therefore adds a third layer of interpretation. It helps convert regression relationships and mechanism propositions into a calibrated stock-flow structure. In this way, the analysis can move from the question of whether a factor matters to the question of how policy combinations accumulate, reinforce, or offset one another over time.

2.3. The Four-dimensional Collaborative Mechanism

The paper adopts the four-dimensional collaborative mechanism proposed in the dissertation. Policy adaptation refers to process listing, rule unification, and administrative closed-loop design. Resource integration refers to the coordinated use of fiscal support, fund-adjustment capacity, organizational resources, and interdepartmental collaboration. Technological empowerment refers to online services, electronic credentials, cross-department data sharing, system support, and rule-engine applications. Regulatory assurance refers to eligibility certification, audit coverage, abnormality identification, accountability tracing, and risk-warning mechanisms.

These four dimensions should not be treated as independent toolboxes. Their relationship is sequential and interactive. Policy adaptation defines the governance boundary and prevents digital tools from being layered over contradictory rules. Resource integration provides the organizational and fiscal carrying capacity for reform. Technological empowerment reduces transaction costs and makes process standardization executable at scale. Regulatory assurance stabilizes reform outcomes by preventing front-end speed from generating back-end risk accumulation. This logic suggests that sustained gains in process efficiency are more likely to emerge from coordination across dimensions than from one-sided interventions.

3. Methodological Design

3.1. Empirical Foundation: Yingkou's Efficiency Structure

The first empirical premise of this paper is that Yingkou's efficiency bottleneck is concentrated in PTE rather than SE. According to the dissertation results, Yingkou's mean PTE during 2015-2024 is 0.60, while its mean SE is 0.89. In the 2020 shock year, PTE fell further to 0.54, whereas SE remained at 0.88. This pattern indicates that fluctuations in overall efficiency were driven mainly by process efficiency. In practical terms, the problem is not simply insufficient resources or an inappropriate pooling scale. Rather, it is the accumulation of institutional friction costs caused by fragmented procedures, inconsistent information standards, weak interdepartmental coordination, repeated verification, and incomplete closed-loop supervision.

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This diagnostic starting point matters because it determines the direction of subsequent optimization. If the principal bottleneck were scale efficiency, then expansion of the pooling base, broader resource input, or more aggressive structural adjustment might be the main response. But when PTE is the core weakness, the more direct policy targets are business-chain redesign, automatic verification, exception handling, and process-performance management.

3.2. System Boundary and Variable Design

Within this problem setting, the system dynamics model takes Yingkou as the core calibration object under the provincial institutional environment. The core stock variables include cumulative fund balance, the number of contributing insured persons, the number of benefit recipients, and governance-capacity stock. The core flow variables include contribution revenue, fiscal subsidies, benefit expenditure, adjustment inflows and outflows, changes in administrative cost, and the effect of risk handling. Auxiliary variables include the contribution base, the growth of ageing pressure, digital penetration, data-sharing capability, audit coverage, and the effectiveness of eligibility certification.

The equation design follows a fund revenue-expenditure main line while embedding the four-dimensional mechanism into key functions. Contribution revenue is shaped not only by the number of contributors and the contribution base, but also by collection efficiency, which is influenced by policy adaptation and technological empowerment. Benefit expenditure depends on the number of recipients, the average benefit level, and payment standardization, which is influenced by regulatory assurance. Administrative-cost intensity may rise with wider coverage but decline with stronger digital substitution and process optimization. Risk exposure is affected by payment scale, eligibility-certification strength, and abnormality-identification capacity. Through this structure, the mechanism propositions are translated into a dynamic simulation framework rather than remaining descriptive statements.

3.3. Scenario Architecture and Model Validation

The scenario design includes a benchmark scenario, four single-dimension policy scenarios, and combination scenarios. The benchmark scenario extends current trends without major additional intervention. The policy-adaptation scenario emphasizes rule sorting, standard unification, and the closure of high-frequency matters. The resource-integration scenario emphasizes fiscal-support optimization, stronger fund-adjustment capacity, and tighter organizational coordination. The technological-empowerment scenario emphasizes online services, electronic credentials, data sharing, and system integration. The regulatory-assurance scenario emphasizes eligibility certification, audit coverage, abnormality identification, and risk-warning closure. Combination scenarios are designed to test whether integrated pathways such as institution plus technology, or rule optimization plus data integration plus regulation, are more stable than isolated measures. [9-10]

Model validation follows the logic described in the dissertation: structural validation of variable directions and feedback links, historical fitting against the 2015-2024 series, extreme-condition testing under conditions such as accelerated ageing or weakened policy support, and sensitivity testing for key elasticity parameters. The purpose is not to identify one perfectly deterministic future path, but to compare the relative logic and sustainability of different governance combinations under realistic constraints.

4. Results and Discussion

4.1. Why PTE Should be the Direct Target of Optimization

The core policy implication of Yingkou's efficiency structure is straightforward: governance reform should aim first at process friction reduction. Figure 1 shows the basic diagnostic fact. Both in the long-run mean and during the 2020 shock year, PTE is substantially lower than SE.

ISSN: 2688-8645

This means that Yingkou's main improvement space lies in the quality of process organization rather than in scale expansion. In the dissertation, this gap is linked to four concrete issues: fragmented administrative processes, inconsistent information standards, insufficient interdepartmental collaboration, and the absence of a stable closed-loop supervision mechanism.

Table 1. Core scenario settings in the SD framework

Scenario	Primary governance lever	Typical instruments	Immediate target	Key caution
Benchmark	Continuation of existing trend	No major additional intervention	Observe baseline evolution	May lock in existing PTE bottlenecks
Policy adaptation	Rule sorting and process closure	Standard lists; one-stop chains; clearer authority	Reduce procedural ambiguity	Weak digital support may limit scale-up
Resource integration	Organizational and fiscal coordination	Fund-adjustment support; departmental coordination	Improve carrying capacity	Effects may be slow without process redesign
Technological empowerment	Digital substitution and data sharing	Online services; electronic credentials; interface opening	Lower transaction costs	May create online-offline layering if rules remain unchanged
Regulatory assurance	Verification and risk closure	Eligibility certification; audits; abnormality warning	Stabilize payment standardization	Pure ex post control can raise correction cost
Combination path	Institution + resources + technology + regulation	Integrated reform packages	Sustain PTE improvement and stability	Requires sequencing and accountability

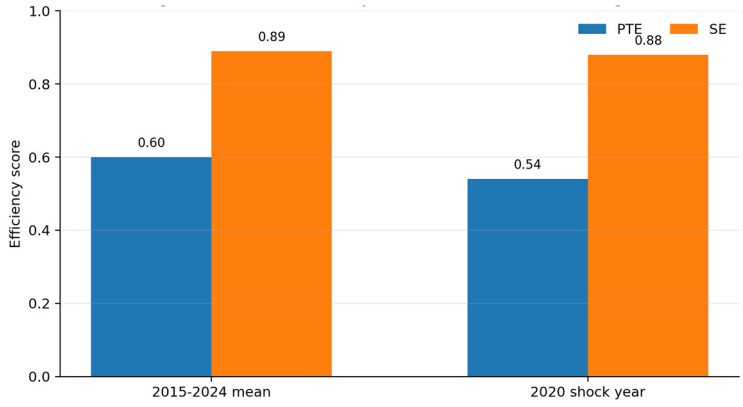

Figure 1. Yingkou's main governance bottleneck is PTE rather than SE

The practical significance of this diagnosis is that it converts an abstract efficiency gap into a task-oriented reform agenda. Instead of focusing on generic expansion, Yingkou should prioritize process nodes where repeated verification, return processing, manual intervention, and delayed abnormality handling are concentrated. In this sense, the improvement of pension

ISSN: 2688-8645

insurance governance should be judged not only by shifts in TE, but also by whether PTE rises in tandem with better process indicators such as automatic-verification coverage, one-stop completion, and lower rates of returned and reprocessed cases.

4.2. From Isolated Digitalization to Coordinated Governance

The second major result concerns the role of digital governance. The dissertation's regression evidence indicates that digital governance, cross-department information sharing, and process standardization have stable positive associations with efficiency improvement. However, this does not mean that digitalization alone is sufficient. The broader mechanism analysis shows that when technology is introduced without rule simplification, standard unification, and regulatory closure, new forms of friction may appear. Online filling may coexist with offline resubmission, connected systems may still rely on manual interpretation, and fast front-end acceptance may only shift unresolved risk to the back end.

From a system dynamics perspective, this is a classic case of incomplete loop closure. Technological empowerment can reduce cost and increase speed, but unless policy adaptation defines clear process boundaries and regulatory assurance keeps verification, audit, and accountability synchronized, the short-term gains of digital tools may not accumulate into sustained governance improvement. This is why the paper emphasizes the four-dimensional mechanism rather than a technology-only strategy. Figure 2 presents this logic: the direct target is process-friction reduction, but the stability of that target depends on the interaction among institutions, resources, technology, and regulation.

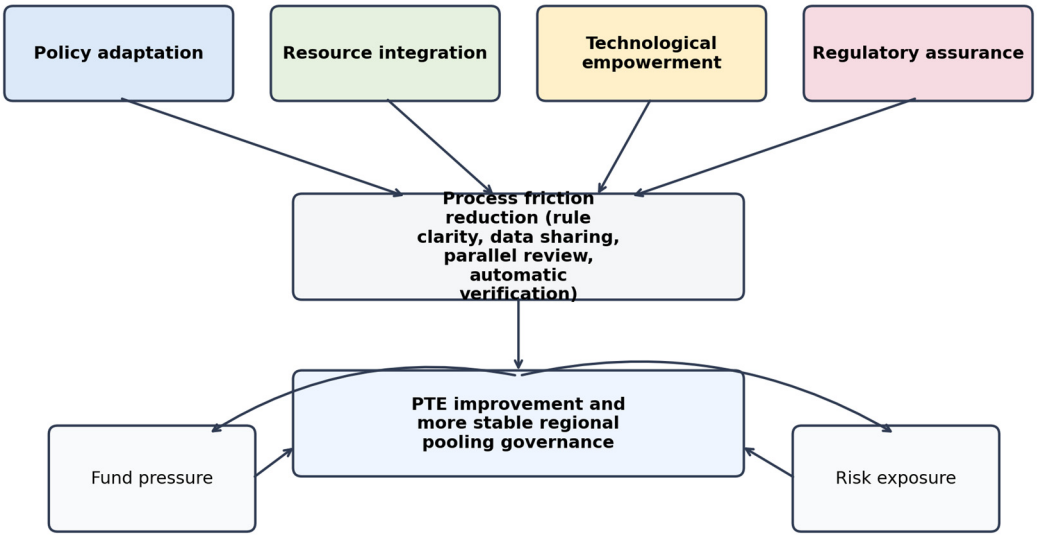

Figure 2. SD-oriented four-dimensional collaborative mechanism for process-friction reduction

4.3. A Phased Optimization Path for Yingkou

The third result is a staged governance path. In the short term, Yingkou should focus on high-frequency matters capable of quickly reducing process friction, especially the closed loop of benefit eligibility certification and one-stop online handling. Eligibility certification is a particularly suitable entry point because it touches multiple data sources, generates frequent verification demands, and has clear implications for both service efficiency and risk control. Through cross-department data sharing and automatic rule-engine verification, repeated checking, return processing, and ex post remediation can be reduced directly.

In the medium term, the reform focus should move toward process reengineering and cross-department data integration. This includes opening the most relevant data chains, especially those related to public-security population data, tax contribution records, and medical-

ISSN: 2688-8645

insurance participation, while gradually extending standardized operational logic to more complex business such as transfer continuation and benefit assessment. In the long term, the key task is institutionalization. Process-performance indicators should be incorporated into routine assessment, risk-warning thresholds should be continuously adjusted, and issue-list and rectification-loop mechanisms should turn reform from a project-based intervention into a stable governance routine. Figure 3 summarizes this staged roadmap.

4.4. Implications for City-level Pension Governance

Table 2. Phased optimization tasks for Yingkou

Stage	Time horizon	Priority tasks	Core process indicators	Expected governance effect
Short term	0-6 months	Eligibility-certification closed loop; standard lists; pilot parallel review	One-stop completion rate; automatic-verification coverage; returned-case ratio	Rapid reduction of high-frequency process friction
Medium term	6-18 months	Data-chain opening; rule-engine codification; transfer and benefit-assessment reengineering	Cross-department verification time; online-substitution rate; share of manual rechecking	Broader PTE improvement and lower coordination cost
Long term	>18 months	Risk-warning thresholds; performance linkage; issue-list and review mechanism	Abnormal-case processing cycle; audit closure rate; stability of PTE and TE	Institutionalization of stable governance capacity

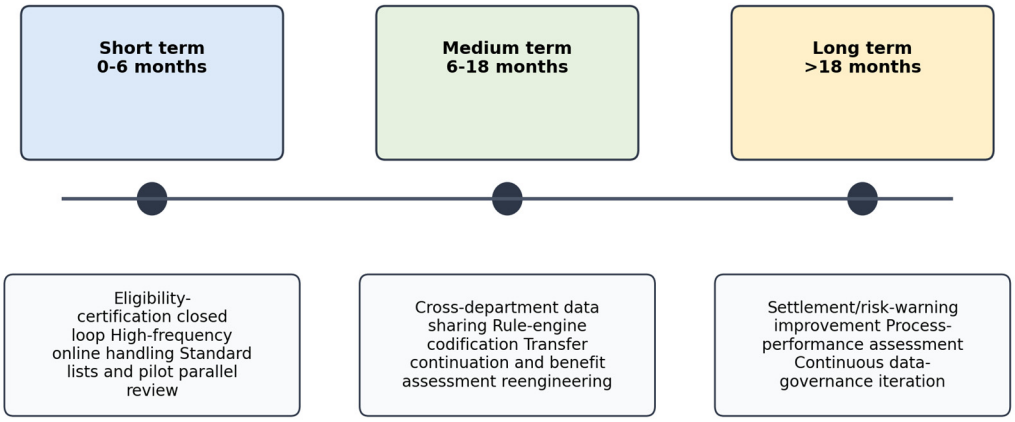

Figure 3. A phased optimization roadmap centered on PTE improvement

The case of Yingkou has implications beyond a single city. Many transformation-oriented cities operate under similar conditions: fluctuating contribution bases, rising ageing pressure, limited fiscal flexibility, and uneven digital foundations. For such cities, the priority should not be to pursue visible platform construction alone. What matters more is whether institutional rules, organizational collaboration, technological tools, and regulatory closure are aligned in a way that directly acts on PTE. This also suggests that the evaluation of digital governance should shift from construction inputs to process performance. Indicators such as online-substitution rate, one-stop completion rate, automatic-verification coverage, returned-case ratio, and abnormal-case processing time are more informative than the number of systems built or the scale of one-off investment.

The broader analytical lesson is that pension insurance efficiency improvement is not a single-point breakthrough but a sequential and conditional process. The earlier stages must remove

the most consequential process losses first; later stages then consolidate these gains through institutionalization and performance linkage. This path is more feasible for middle-tier cities because it balances the cost-benefit ratio of reform with organizational carrying capacity.

5. Conclusion

This paper has examined how system dynamics can be used to optimize city-level pension insurance pooling governance in Yingkou under unified provincial pooling rules. Starting from the dissertation finding that Yingkou's main weakness lies in PTE rather than SE, the paper has shown why a process-centered governance path is more appropriate than a scale-centered response. It further demonstrated that the most promising route is not isolated digitalization but a four-dimensional collaborative mechanism combining policy adaptation, resource integration, technological empowerment, and regulatory assurance.

Three conclusions stand out. First, the direct policy target in Yingkou should be the reduction of process friction in high-frequency and verification-intensive links. Second, technology can improve efficiency only when it is embedded in clarified rules, interoperable standards, and closed-loop regulation. Third, a phased roadmap from pilot closure to system integration and then to institutionalized performance management is more likely to yield stable medium-term gains than one-off reform campaigns.

The paper also has limits. Because the current article is derived from dissertation evidence and publicly accessible city-level materials, it does not yet incorporate fine-grained process logs such as repeated-submission rates or detailed case-handling times. Future studies could combine administrative trace data with simulation modelling to achieve more precise node-level diagnosis. Even so, the present study shows that system dynamics is highly useful for extending pension insurance efficiency research from measurement and explanation to pathway comparison and policy design.

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