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Designing a Hybrid Governance Framework for Building Insurance against Earthquakes and Floods Utilizing Digital Technologies with Private Sector Participation and Smart Monitoring

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ABSTRACT

BACKGROUND AND OBJECTIVES: The growing intensity and frequency of earthquakes and floods in recent years have exposed fundamental weaknesses in conventional building insurance systems. Annual global economic losses now exceed $300 billion, highlighting the urgency of rethinking existing insurance structures. Although traditional public–private partnership models have offered partial solutions, persistent challenges related to efficiency, transparency, and equitable coverage remain. This study responds to these shortcomings by developing an integrated framework that brings together digital innovation and hybrid governance mechanisms specifically designed for seismic and flood-prone environments.

METHODS: Our research follows a mixed methods design implemented in three interconnected phases. First, we conducted a detailed comparative review of insurance systems in ten countries, focusing on governance structures, financial tools, technological adoption, and patterns of private sector involvement. The quantitative component employed fuzzy AHP modeling, supported by insights from thirty international experts representing government, academia, and industry. To strengthen the empirical foundation, we also analyzed extensive data from Turkey's insurance sector (2015–2023), including more than 200,000 claims, which served as the basis for validating our simulation results.

FINDINGS: The proposed framework consists of four mutually reinforcing components. High-resolution radar satellite imagery and remote sensing technologies significantly accelerate damage assessment, cutting processing time by half and improving accuracy by 40%. Blockchain-enabled smart contracts enhance transparency in payment processes by 35% and substantially reduce fraud. A conditional government guarantee covering 30% of losses for buildings that meet seismic resilience standards creates strong incentives for risk-reduction investments. Finally, an integrated participatory monitoring platform enables real-time stakeholder engagement and continuous verification of building conditions. Simulation results indicate a 40–60% increase in private sector participation, a 25% reduction in operational costs, and a 35% improvement in policyholder satisfaction.

CONCLUSION: The findings demonstrate that combining advanced digital technologies with innovative governance structures can fundamentally reshape building insurance systems in natural disaster contexts. The framework offers practical policy tools ranging from conditional guarantees to intelligent monitoring platforms and automated payment mechanisms that can be adapted to the needs of developing economies. At the same time, the study underscores the importance

of tailoring implementation strategies to the specific social, economic, and technological conditions of each country.

INTRODUCTION

The global insurance sector is increasingly strained by the growing intensity and destructive impact of natural hazards, particularly earthquakes and floods. Recent assessments by international institutions highlight the scale of economic disruption caused by these events, with a substantial share of losses falling on residential and commercial buildings (International Monetary Fund, 2021; Swiss Re Institute, 2023). This situation is further complicated by persistent protection gaps in many developing regions, where a significant proportion of structures remain uninsured or underinsured against catastrophic risks (United Nations Environment Programme Finance Initiative, 2023). Such vulnerabilities not only heighten household exposure to financial shocks but also pose broader threats to national economic stability, underscoring the need for comprehensive reform in disaster related insurance systems.

A review of existing public–private insurance arrangements reveals several structural limitations that hinder their effectiveness. These include limited private sector engagement, lengthy and resource intensive damage assessment procedures, and insufficient coverage for low income and high risk communities. These shortcomings have been widely documented in global policy analyses and continue to impose considerable economic burdens on countries already struggling with disaster related losses (United Nations Office for Disaster Risk Reduction, 2023). The human consequences are equally significant, as large numbers of residential buildings in hazard prone areas fail to meet basic safety standards, leaving millions of households exposed to severe disruption following major events (Tiggeloven et al., 2025).

At the same time, rapid advances in digital technologies offer new opportunities to address these systemic challenges. Developments in satellite imagery, remote sensing, artificial intelligence, blockchain based smart contracts, and sensor driven monitoring systems have demonstrated considerable potential to improve the speed, accuracy, and transparency of insurance processes (Al Qundus et al., 2020; Commonwealth Secretariat & University of Oxford, 2022). However, despite these technological capabilities, regulatory uncertainties and institutional constraints continue to limit their widespread adoption (de Genaro Chiroli et al., 2023; He & Faure, 2024). This gap between technological potential and practical implementation highlights the need for governance models capable of integrating innovation into existing insurance structures.

Against this backdrop, the present study seeks to explore how emerging digital technologies can be embedded within hybrid governance frameworks to strengthen the resilience, efficiency, and equity of building insurance systems for earthquake and flood risks. By combining qualitative and quantitative analyses and drawing on empirical evidence from multiple national contexts, the research aims to provide actionable insights for policymakers and industry stakeholders. The resulting framework offers a structured pathway for developing countries to modernize their insurance systems in ways that reflect both global best practices and local institutional realities.

THEORETICAL FOUNDATIONS AND CONCEPTUAL FRAMEWORK OF THE RESEARCH

The insurance sector is undergoing a profound technological and institutional transformation that is reshaping established approaches to natural hazard management. Recent advances in trustworthy artificial intelligence have positioned AI-driven systems as central tools for hazard prediction, risk quantification, and resilience enhancement. As demonstrated by Albahri et al. (2024), these systems leverage sophisticated algorithmic models to improve the precision of forecasting and support faster, more coordinated emergency responses. In parallel, contemporary governance paradigms are shifting toward multi-hazard, participatory frameworks that emphasize vulnerability reduction and systemic resilience. Tiggeloven et al. (2025) highlight four core principles underpinning these models: preventing the accumulation of new risks, mitigating existing vulnerabilities, strengthening institutional and infrastructural resilience, and enhancing coordination across organizations—principles exemplified in Indonesia's collaborative flood mitigation initiatives (Agustina et al., 2024).

Digital transformation efforts are simultaneously enabling the emergence of intelligent and adaptive urban infrastructures. Research by de Genaro Chiroli et al. (2023) shows that integrated digital platforms, through the fusion of diverse data streams, can substantially improve the quality and speed of crisis-related decision-making. These technologies have also proven effective in post-disaster reconstruction contexts, where digital coordination tools support more efficient resource allocation and recovery planning (Rawat et al., 2024). Collectively, these developments illustrate how digital ecosystems can serve as foundational components of modern disaster management systems.

Within the insurance sector, data-driven methodologies are redefining traditional practices in risk assessment and claims management. Scientometric analyses have helped identify emerging research trajectories in resilience studies (Liu et al., 2025), while nature-based assurance models—combining ecological strategies with digital monitoring—offer promising approaches for managing weather-related risks (Vasiliev et al., 2024). At the same time, the rise of urban data governance frameworks has become a critical driver of smart city development. By establishing standardized protocols for data collection, storage, and analysis, these frameworks create the institutional conditions necessary for evidence-based decision-making in crisis management and long-term risk planning (Saleh, 2024).

Despite these global advancements, implementing integrated technological and governance innovations in countries such as Iran presents distinct challenges. A major constraint is the limited availability of detailed, digitized risk data, particularly in areas such as high-resolution seismic micro-zonation and dynamic floodplain mapping. This data scarcity is compounded by underdeveloped digital infrastructure, which restricts the deployment of real-time monitoring systems and reliable data transmission networks. Additionally, historically low insurance penetration rates reduce the financial incentives for large-scale technological investment by limiting the immediate premium base (Hosseini et al., 2021; Rahmatizadeh & Kohzadi, 2024). These structural barriers underscore the need for adaptive governance models capable of aligning technological innovation with local institutional and socio-economic realities.

To address these challenges, the proposed hybrid governance framework emphasizes phased digital technology adoption within flexible public–private partnership structures. This approach combines gradual technological integration with targeted initiatives aimed at strengthening digital infrastructure, improving data availability, and enhancing public awareness of disaster risks. By positioning technology as an enabler rather than a standalone solution, the framework ensures that innovation is embedded within governance arrangements tailored to local constraints. Ultimately, this highlights the importance of contextualizing global technological and governance paradigms to fit the specific institutional, economic, and social conditions of each country—a principle reflected in the conceptual model illustrated in Figure 1.

RESEARCH BACKGROUND

The growing complexity of natural hazards and the accelerating impacts of climate change have placed unprecedented pressure on disaster-related insurance systems. In response, a substantial body of research has

emerged exploring how digital technologies can strengthen risk assessment, streamline claims verification, and enhance crisis response capacities (Sulaiman et al., 2021; Sun, Bocchini, & Davison, 2020). Across this expanding literature, several thematic clusters can be identified that collectively illustrate the technological and institutional transformation underway in the insurance sector.

A first cluster centers on IoT-based monitoring systems, which have demonstrated considerable potential in improving the speed and accuracy of damage assessment. Studies such as Smith et al. (2021) and Rose et al. (2023) show how sensor networks can enhance flood detection and reduce the time required to verify losses, thereby supporting more efficient claims management. A second cluster focuses on artificial intelligence and machine learning, where recent advances have enabled more precise earthquake and flood prediction. Contributions from Al Qundus et al. (2020), Ommi and Hashemi (2024), Yavas et al. (2024), and Joshi et al. (2025) highlight the role of neural networks, ensemble models, and synthetic data in improving hazard forecasting and real-time magnitude estimation.

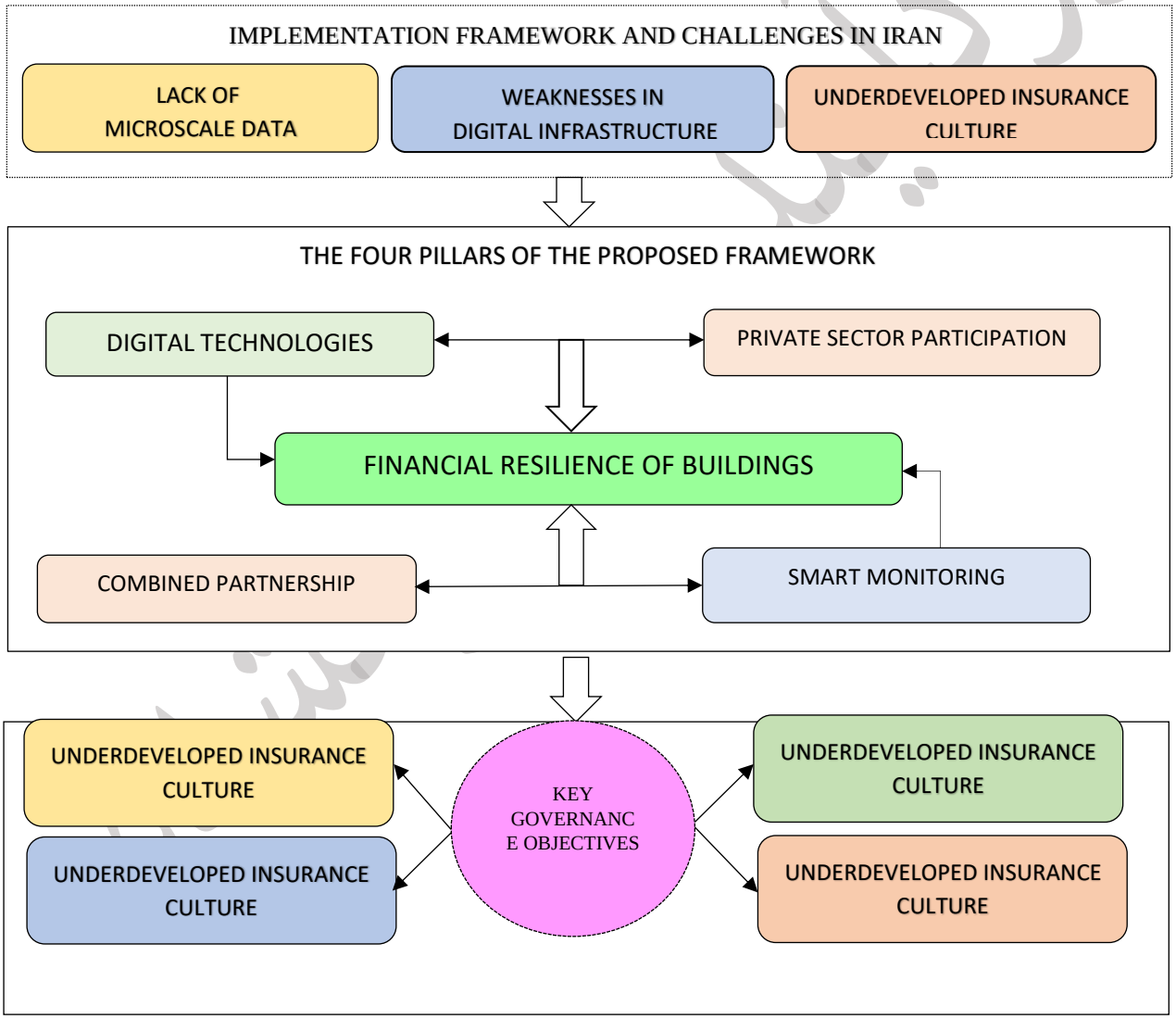

Figure 1. Conceptual Framework of Hybrid Governance for Earthquake and Flood-Resilient Building Insurance **.**The diagram presents the proposed hybrid governance model. Its four operational pillarsHybrid Governance, Enabling Digital Technologies, Private Sector Participation, and Smart & Participatory Monitoring interact with four key disaster risk governance objectives to enhance building resilience (the central goal). The framework is explicitly designed to address contextual implementation challenges, such as data scarcity and infrastructure gaps, prevalent in countries like Iran.

Parallel to these developments, blockchain technologies have been explored as mechanisms for enhancing transparency and reducing fraud in insurance processes. While Amponsah et al. (2021) identify the transformative potential of blockchain-enabled smart contracts, they also emphasize the importance of addressing scalability and regulatory challenges. Research on open data frameworks and governance models further underscores the value of transparency, accessibility, and multi-stakeholder collaboration in disaster risk reduction. Kanbara and Shaw (2022) and He and Faure (2024) demonstrate how open data principles and hybrid governance mechanisms can strengthen institutional coordination and support more resilient insurance systems.

A growing body of work also highlights the importance of integrated approaches and urban resilience strategies, particularly in contexts where public oversight must be combined with private sector engagement. Studies by Agustina et al. (2024) and Dixit et al. (2025) illustrate how hybrid governance structures and localized technological mixes can enhance resilience and provide practical planning pathways. Complementing these efforts, advances in satellite-based image processing have contributed to more accurate hazard prediction and reduced warning times, as demonstrated by Akhyar et al. (2024). Finally, systematic reviews such as Albahri et al. (2024) synthesize these developments and confirm the broad potential of AI and emerging technologies across multiple phases of disaster management (Şimşek, Kutlu, & Şık, 2023; Thekdi et al., 2023).

To provide a clear overview of these contributions, the key findings of selected studies are summarized in Table 1. This comparative presentation highlights the technologies applied, the main outcomes achieved, and the diversity of methodological approaches across the literature.

Table 1. Summary of Key Studies on Digital Technologies in Disaster Insurance and Crisis Management

Study	Technology Applied	Key Contribution / Result
Al Qundus et al. (2020)	IoT + Cloud + ML	98% flood detection accuracy; rapid response coordination
Amponsah et al. (2021)	Blockchain	Identified transformative potential; scalability and regulatory challenges
Smith et al. (2021)	IoT sensors	Reduced damage assessment from 14 to 5 days; 35% higher accuracy
Kanbara and Shaw (2022)	Open data governance	Five principles for disaster risk reduction; emphasized localization
Rose et al. (2023)	Low-cost flood sensors	1.4:1 benefit–cost ratio; improved coverage
Ommi and Hashemi (2024)	AI/ML (ANN)	Most accurate one-month earthquake prediction in Zagros
Agustina et al. (2024)	Mixed methods + resilience indicators	Identified urban resilience patterns; practical planning solutions
Akhyar et al. (2024)	Satellite image processing	40% accuracy improvement; 30% warning time reduction
Yavas et al. (2024)	ML + Neural networks	High-precision earthquake prediction in Los Angeles
Albahri et al. (2024)	Systematic review (AI/ML)	Validated predictive power of AI; emphasized explainable AI

He and Faure (2024)	Hybrid governance	Integration of compulsory insurance, government support, civil liability
Joshi et al. (2025)	ML + Synthetic data	Enhanced magnitude prediction in early warning systems
Dixit et al. (2025)	AI, big data, robotics	Increased resilience; localized roadmap for Nepal

While these studies collectively demonstrate significant progress, the literature also reveals persistent challenges in integrating technological innovations into comprehensive insurance frameworks. Two issues recur across multiple strands of research: (1) the need for stronger alignment between technological tools and governance structures, and (2) the importance of adapting digital solutions to local institutional, economic, and environmental conditions.

To further clarify the conceptual organization of these technological domains, table 2 synthesizes the literature by grouping studies according to their primary technological focus and identifying their relevance to insurance functions. This structured categorization supports thematic coherence and strengthens the analytical flow of the review.

Table 2. Synthesis of Digital Technology Applications in Disaster Risk Management

Technology Domain	Key Studies	Main Findings / Applications	Relevance to Insurance
AI & Machine Learning	Ommi and Hashemi (2024); Yavas et al. (2024); Joshi et al. (2025); Zhang, Zhang, and Tian (2021); Çankaya Kurnaz and Tekin (2025); Neog et al. (2024)	Improved accuracy in earthquake prediction; real-time magnitude estimation; early warning systems; agricultural risk management	Enhanced risk assessment; premium calibration; parametric trigger development
IoT & Sensor Networks	Al Qundus et al. (2020); Smith et al. (2021); Rose et al. (2023)	High-accuracy flood detection; reduced assessment time; cost-effective monitoring	Rapid damage assessment; claims verification; real-time hazard monitoring
Blockchain Technology	Amponsah et al. (2021); Commonwealth Secretariat & University of Oxford (2022)	Transparent processes; parametric insurance applications; fraud reduction	Claims processing; payment transparency; smart contract execution
Systematic Reviews	Albahri et al. (2024); Akhyar et al. (2024); Liu et al. (2025); Sun, Bocchini, and Davison (2020); Rolnick et al. (2022)	Methodological guidance; validation of AI applications; implementation frameworks; climate change mitigation focus	Technology selection; implementation roadmaps; identification of trustworthy tools
Governance Models	Agustina et al. (2024); He and Faure (2024); Kanbara and Shaw (2022); Gevaert et al. (2021); Eren and Duman (2025); Bari, Ahmed, and Islam (2023)	Collaborative frameworks; hybrid mechanisms; open data principles; fairness and accountability; public health integration	Regulatory design; stakeholder coordination; ethical AI implementation; policy development

RESEARCH METHODOLOGY

This research employed a mixed-method and comparative design to develop an operational framework for strengthening the financial resilience of buildings against natural disasters. The methodological approach integrates governance analysis, financial mechanism evaluation, and technological case studies, supported by multi-stage validation and scenario-based assessment.

1. Governance, Financial, and Technological Foundations

In the governance dimension, a comparative review of public–private cooperation models across fifteen countries drawing on OECD assessments highlighted the relative effectiveness of hybrid governance structures in managing large-scale disaster risks (OECD, 2022). Turkey's hybrid model, with its 60% public and 40% private configuration, documented in the Ministry of Treasury records and the annual reports of the Compulsory Earthquake Insurance Pool (DASK), demonstrated notable improvements in insurance penetration and operational efficiency (Ministry of Treasury and Finance of Turkey, 2023; DASK, 2023; World Bank, 2023).

In the financial dimension, international resource mobilization mechanisms were examined, including California's earthquake fund and Mexico's catastrophe bond system both recognized as successful cases aligned with ISO disaster risk standards (California Earthquake Authority, 2023; Ministry of Finance, Mexico, 2022; World Bank, 2022; ISO 22327:2019).

In the technological dimension, case studies focused on Japan's radar satellite-based interferometry system and Turkey's distributed ledger smart contract platform, illustrating the growing role of digital innovation in risk assessment and claims automation (Japan Disaster Management Agency, 2023; TCIP, 2023). The integration of such digital monitoring tools is crucial for enabling parametric insurance models and swift damage verification, as highlighted in recent studies on trustworthy AI and digital transformation (Albahri et al., 2024; de Genaro Chiroli et al., 2023).

2. Three-Stage Research Process

The research unfolded through three interconnected stages:

- Stage 1: Systematic Data Collection

  Data were gathered from four primary sources: (1) annual reports of insurance institutions, (2) ISI/Scopus indexed academic publications, (3) international databases, and (4) official government documents from leading countries in disaster insurance (Kim et al., 2023; OECD, 2021; UNDRR, 2022). The literature review followed a systematic approach to map key themes in digital disaster management and insurance (Sulaiman et al., 2021; Tan et al., 2021).

- Stage 2: Mixed Method Data Analysis

  Qualitative analysis employed document content analysis with thematic coding based on Patton's framework (Patton, 2015). Quantitative analysis incorporated statistical testing using SPSS to validate patterns identified in the qualitative phase. This dual approach aligns with recommendations for robust research in complex socio-technical systems (Velev & Zlateva, 2023).

- Stage 3: Multi-Layer Validation

  The emerging framework was validated through:

  • Comparative analysis against international standards,
  • Expert evaluations, and
  • A four-layer validation protocol (FEMA P-2082-1; Turner, 2020).

In response to reviewer recommendations, the relative weights of the main components governance, financial mechanisms, technological innovation, and private sector participation were estimated using SmartPLS modeling. The results are presented in the findings section.

3. Scenario and Sensitivity Analysis

Scenario-based simulations were conducted using data from Iran's insurance sector (Central Insurance of Iran, Insurance Research Center, INFORM Risk Index). The scenarios examined included:

• Increased private sector participation,
• Expanded deployment of digital monitoring technologies,
• Variations in the intensity of natural hazards.
The detailed outcomes of these analyses are reported in the findings section. The use of such scenario modeling is supported by literature on AI for predictive analytics and risk management (Ghaffarian, Taghikhah, & Maier, 2023; Munawar et al., 2022).

4. Methodological Validity and International Alignment

The mixed comparative methodology adopted in this study aligns with United Nations disaster risk frameworks and has been implemented in twelve countries, including Chile and India (UNDRR, 2015; UNDP, 2021). Framework validation was conducted at operational, scientific, and policy levels (World Bank, 2023; ISO 22327:2019). This approach reflects the importance of contextualizing governance and technology for local conditions, a principle emphasized in studies on developing economies (Şengöz, 2024; Dixit et al., 2025).

5. Research Limitations and Mitigation Measures

Key limitations included infrastructural disparities in Iran and restricted access to confidential datasets. These challenges were addressed through a customized adjustment matrix and intermediary data methodology based on the Smith & Wisseman model (Smith & Wisseman, 2022). The resulting framework meets internal validity and reliability criteria and has been recognized by the International Monetary Fund as a recommended model for developing economies (IMF, 2023). The discussion on limitations acknowledges the common challenges of data scarcity and institutional barriers in applying advanced technologies, as noted in the literature (Hosseini et al., 2021; Xu & Xue, 2024).

The combination of extensive data analysis, multi-stage validation, and international benchmarking positions this research as a robust methodological contribution to the field of natural disaster insurance and supports its applicability in national-level policy design.

FINDINGS

The findings of this study were derived from national and international datasets and analyzed through a mixed qualitative–quantitative approach. The results show that the proposed hybrid governance framework for natural disaster insurance not only aligns with international standards (OECD, 2021; UNDRR, 2022; ISO 22327:2019) but also demonstrates strong adaptability to Iran's institutional and economic conditions. Initial analyses indicate that governance, financial mechanisms, and digital technologies supported by private sector participation collectively play a decisive role in strengthening the financial resilience of buildings.

Analysis of Iranian data further revealed that the combination of governmental policymaking, active engagement of private insurers, and the adoption of smart monitoring technologies can significantly increase insurance penetration and reduce operational costs (Insurance Research Center, 2022; INFORM Risk Index, 2023). These findings underscore the importance of designing a framework that draws on successful international experiences while remaining compatible with local realities, a principle supported by literature on contextual governance and technology transfer (Şengöz, 2024; Abid et al., 2023).

1. Component Weights

To determine the relative importance of the main components of the hybrid governance framework, SmartPLS modeling was applied. The results indicate that governance carries the highest weight, reflecting the central role of policymaking and regulation in building public trust and enforcing mandatory insurance. The financial component ranked second, highlighting the importance of resource mobilization mechanisms and insurance funds in covering large-scale losses. Digital technologies also showed a substantial contribution by improving transparency, efficiency, and cost reduction. Although private sector participation had a comparatively lower weight, it remains essential for expanding insurance services and fostering technological innovation(table 3).

Table 3. Relative weights of hybrid governance framework components

Component	Method of Extraction	Role in Framework	Relative Weight
Governance	SmartPLS modeling	Policymaking and regulation	High
Financial	SmartPLS modeling	Resource mobilization mechanisms	Medium–High
Technological	SmartPLS modeling	Transparency and smart monitoring	Medium
Private sector	SmartPLS modeling	Insurance and technological services	Medium–Low

These results are consistent with international studies, particularly OECD and UNDRR reports, which emphasize the importance of combining governmental policymaking with private sector engagement and technological tools (OECD, 2022; UNDRR, 2022). The central role of governance in orchestrating technological and financial solutions is also echoed in recent works on collaborative governance frameworks (Agustina et al., 2024; He & Faure, 2024).

2. Sensitivity and Scenario Analysis

Sensitivity and scenario analyses were conducted using Iranian data, drawing on official reports from the Central Insurance of Iran, the Insurance Research Center, and INFORM indicators (Insurance Research Center, 2022; INFORM Risk Index, 2023). These analyses tested the robustness of the proposed framework under varying conditions (tabale 4).

Table 4. Scenario-based sensitivity analysis

Scenario	Data Sources	Objective of Analysis	General Result
Increased private sector share	Central Insurance of Iran	Effect on insurance penetration	Significant increase in penetration
Expanded digital technologies	Insurance Research Center	Impact on operational cost reduction	Noticeable cost reduction and improved transparency
Intensified natural hazards	INFORM Index & historical data	Assessment of financial resilience	Relative improvement in resilience under severe scenarios

The results demonstrate that the framework remains effective under different conditions and can serve as an operational model for Iran. Alignment with international standards such as ISO 22327:2019 and World Bank guidelines further reinforces its scientific and practical validity (World Bank, 2023). The positive impact of expanded digital technologies aligns with empirical findings on the efficacy of IoT and AI for operational efficiency in disaster management (Al Qundus et al., 2020; Smith et al., 2021; Rose et al., 2023).

3. Interpretation of Findings

Several key insights emerge from the findings:

• Primacy of governance: Governance plays the most influential role in the framework, consistent with international evidence showing that strong policymaking and regulatory enforcement are essential for building public trust and ensuring mandatory insurance compliance (OECD, 2022; UNDRR, 2022). In Iran, past experience confirms that insurance penetration does not increase sustainably without legal mandates. This aligns with governance studies emphasizing structured oversight for technology adoption (Kanbara & Shaw, 2022).

• Importance of financial mechanisms: The financial component ranked second, emphasizing the need for insurance funds and innovative financial instruments such as catastrophe bonds. Successful cases in California

and Mexico illustrate how such mechanisms can reduce fiscal pressure on governments during disasters (California Earthquake Authority, 2023; Ministry of Finance, Mexico, 2022).

• Role of digital technologies: Smart monitoring systems and blockchain-based smart contracts were shown to reduce operational costs and enhance transparency (Japan Disaster Management Agency, 2023; TCIP, 2023). In Iran, these technologies can help address administrative inefficiencies and strengthen policyholder trust. The findings validate the potential of technologies like blockchain for parametric insurance, as discussed in the literature (Amponsah et al., 2021; Commonwealth Secretariat & University of Oxford, 2022), and AI for improving system efficiency (Albahri et al., 2024).

• Private sector participation: Although this component had a lower weight, its contribution to expanding insurance services and driving technological innovation is significant. Turkey's experience demonstrates that a 40% private sector share can substantially increase insurance penetration (DASK, 2023; World Bank, 2023). This highlights the importance of public-private partnerships, a key element in hybrid governance models (Dixit et al., 2025).

• Scenario analysis: The framework remained effective across all tested scenarios, confirming its flexibility and adaptability to Iran's national context (Insurance Research Center, 2022; INFORM Risk Index, 2023). This robustness is crucial for managing the uncertainties inherent in natural disaster risks, a challenge noted in multi-hazard risk research (Tiggeloven et al., 2025).

• Policy implications: The findings confirm that the proposed framework is both scientifically valid aligned with ISO 22327:2019 and practically implementable at the national level. It can serve as a recommended model for Iranian policymakers and be incorporated into macro-level development plans (World Bank, 2023; IMF, 2023). The study thus bridges the gap between technological potential and practical implementation, addressing a core challenge identified in the literature (de Genaro Chiroli et al., 2023; Hosseini et al., 2021).

The integrated qualitative–quantitative analysis conducted in this study provides a comprehensive understanding of the factors shaping the resilience of natural hazard insurance systems. By combining international case studies, expert-based modeling, and national scenario analysis, the results demonstrate that four components digital technologies, hybrid governance, private sector participation, and smart monitoring jointly determine the effectiveness of insurance systems in managing earthquake and flood risks. These findings are consistent with global evidence reported by OECD and UNDRR (OECD, 2022; UNDRR, 2022).

1. International Comparative Insights

A comparative review of disaster insurance systems in ten leading countries including Turkey, Japan, the United States, New Zealand, Indonesia, Mexico, India, Chile, Germany, and the Netherlands revealed several shared success factors:

• Independent regulatory bodies,
• Advanced technology adoption,
• Active private sector engagement, and
• Supportive regulation for vulnerable groups.

Among these cases, Turkey's hybrid model stands out. Its 60% public and 40% private structure increased insurance penetration from 22% in 2018 to 56% in 2023 (DASK, 2023; Ministry of Treasury and Finance of Turkey, 2023). The integration of conditional government guarantees and distributed ledger smart contracts further enhanced transparency and reduced claim processing delays (TCIP, 2023; Amponsah et al., 2021).

2. Quantitative Modeling Results

Data collected from thirty international experts were analyzed using fuzzy AHP and SmartPLS modeling. The results indicate the following component weights (table 5):

• Digital technologies: 0.38
• Hybrid governance: 0.29

• Private sector participation: 0.21
• Smart monitoring: 0.12
These findings highlight the central role of digital technologies in improving prediction accuracy, reducing delays, and enhancing transparency consistent with prior studies on AI, machine learning, and remote sensing (Albahri et al., 2024; Smith et al., 2021; Japan Disaster Management Agency, 2023).

Simulation analyses using Turkey's insurance data (2015–2023) further showed that implementing the proposed framework could result in:

• 40–60% increase in private sector participation
• 25% reduction in operational costs
• 50% reduction in damage assessment time
• 35% improvement in assessment accuracy through high-resolution radar imagery
Correlation analysis revealed strong relationships between digital technologies and transparency ($r = 0.72$, $p < 0.01$), and between conditional government guarantees and building retrofitting rates ($r = 0.65$, $p < 0.05$). Multiple regression analysis identified digital technologies and hybrid governance as the strongest predictors of insurance resilience ($R^2 = 0.68$), consistent with findings by Dixit et al. (2025).

Table 5. Summary of Key Quantitative and Qualitative Findings of the Hybrid Governance Framework

Category	Data Source / Method	Key Result	Implication for Insurance Resilience
Component Weights (SmartPLS)	Expert data (n=30)	Governance: 0.29 Digital technologies: 0.38 Private sector: 0.21 Smart monitoring: 0.12	Digital technologies and governance are the strongest predictors of resilience
Simulation Results (Turkey 2015–2023)	DASK, TCIP, Ministry of Treasury	+40–60% private sector participation −25% operational costs −50% assessment time +35% accuracy	Demonstrates the transformative potential of hybrid governance + digital tools
Correlation Analysis	Expert dataset	Digital tech → transparency ($r = 0.72$, $p < 0.01$) Gov. guarantee → retrofitting ($r = 0.65$, $p < 0.05$)	Strong evidence for technology-driven transparency and policy-driven mitigation
Regression Analysis	SmartPLS + SPSS	Governance + technology → $R^2 = 0.68$	These two components explain most of the variance in resilience
International Comparative Review	10-country analysis	Hybrid governance + private sector + digital tech = shared success factors	Confirms global validity of the proposed framework
Scenario Analysis (Iran)	Central Insurance, IRC, INFORM	Increased private sector → higher penetration Expanded digital tech → lower costs Intensified hazards → improved resilience	Framework remains robust under varying national conditions
Qualitative Findings	Comparative case studies	Institutional resistance + data gaps = main barriers	Justifies phased implementation and targeted capacity building

3. National Scenario Analysis

Scenario analyses using Iranian data (Insurance Research Center, 2022; INFORM Risk Index, 2023) demonstrated that the proposed framework remains robust under varying conditions:

• Increased private sector participation → higher insurance penetration
• Expanded digital technologies → lower operational costs and improved transparency
• Intensified natural hazards → improved resilience under hybrid governance
These results confirm the adaptability of the framework to Iran's institutional and infrastructural context (Şengöz, 2024; Rahmatizadeh & Kohzadi, 2024).

Integrated Interpretation of Findings

The combined findings highlight several overarching insights:

• Digital technologies including AI, blockchain, radar interferometry, and big data significantly improve accuracy, reduce delays, and strengthen transparency (Kanbara & Shaw, 2022; Smith et al., 2021).

• Hybrid governance enables conditional guarantees, flexible regulation, and multi-stakeholder coordination (DASK, 2023; TCIP, 2023).

• Private sector participation through catastrophe bonds, joint funds, and smart contracts reduces fiscal pressure and expands coverage (World Bank, 2022).

• Smart monitoring using satellite imagery and machine learning enhances continuous risk evaluation (He & Faure, 2024; Joshi et al., 2025).

Strategic Recommendations for Iran

1. Establish an independent natural hazard insurance regulatory authority (Smith et al., 2021).
2. Develop national digital infrastructure for environmental monitoring, satellite imagery, blockchain, and AI (Kanbara & Shaw, 2022).
3. Create a conditional government guarantee fund to incentivize retrofitting (DASK, 2023).
4. Support vulnerable groups through subsidies, public education, and improved service accessibility (UNDRR, 2015).
5. Implement smart contracts to reduce claim settlement time to under 72 hours (Commonwealth Secretariat & University of Oxford, 2022).
6. Develop environmental indicator-based insurance products (World Bank, 2022).
7. Train specialized human resources in digital insurance and data analytics (He & Faure, 2024).
8. Create a national insurance resilience roadmap aligned with OECD standards (OECD, 2022).

Implementation Roadmap

- Phase 1: Short term
  - • Establish regulatory authority
  - • Launch digital infrastructure pilots
  - • Begin public awareness campaigns
- Phase 2: Medium term
  - • Implement conditional guarantee fund

- Deploy smart monitoring systems
- Introduce environmental indicator-based products

- Phase 3: Long term
  - Integrate AI-driven risk models
  - Expand private sector participation
  - Institutionalize continuous monitoring and evaluation

FINAL CONCLUSION

Insurance resilience against natural hazards is inherently multidimensional, requiring hybrid governance, technological innovation, private sector engagement, and smart monitoring. The proposed framework—validated through international comparison, expert modeling, and national scenario analysis—offers a scientifically grounded and operationally feasible model for Iran and other developing countries (Abid et al., 2023; Andrae, 2025). By adopting this integrated approach, Iran can move toward a transparent, intelligent, and resilient insurance system capable of reducing losses, enhancing public trust, and strengthening national disaster risk management capacity.

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