Journal of Economics Intelligence and Technology

ISSN(Online): 3082-3994

ISSN (Print): 3082-3986

Volume- 02| Issue- 02| 2026

Research Article **Received:** 20-05-2026 | **Accepted:** 15-06-2026 | **Published:** 01-07-2026

Advanced Actuarial Modelling in U.S. Insurance and Financial Systems: Strengthening Solvency, Reserve Adequacy, and Systemic Risk Management

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Abstract: The growing complexity of the U.S. insurance industry has revealed the shortcomings of the traditional actuarial methods of assessing solvency, reserve adequacy, and systemic risk management. This integrative review, drawing on over 50 peer-reviewed articles, regulatory publications, actuarial standards, and institutional reports spanning 2019 to 2026, examines the impact of advanced actuarial modelling techniques, such as Principle-Based Reserving, stochastic modelling, machine learning, and systemic risk analytics, on risk assessment in the insurance and financial sectors in the United States. The review draws on evidence from three inter-related areas: solvency, reserve adequacy, and systemic risk. The results indicate that significant advancement has been made, especially in the improvement of risk sensitivity of capital adequacy assessment, more advanced stress testing of scenarios, improved identification of tail risk and emerging vulnerabilities, and increased precision of systemic risk monitoring at the entity and macroprudential levels. However, there are still challenges to be addressed in terms of model integration, regulatory consistency, and governance of emerging technologies. The review finds that the concepts of solvency, reserving, and systemic risk are interconnected, and approaches that consider them separately may not properly capture sources of vulnerability. More integrated actuarial frameworks are therefore needed to strengthen financial resilience, improve risk oversight, and address the structural changes reshaping the U.S. insurance sector.

Keywords: Actuarial Modelling, Solvency, Reserve Adequacy, Systemic Risk, Principle-Based Reserving, Insurance Regulation.

INTRODUCTION

The U.S. insurance industry is integral to the national financial system, helping to ensure the stability of households, the continuity of businesses, and the resilience of the economy by offering mechanisms for transferring risk. The industry has assets valued at more than $10 trillion and is one of the largest institutional investors in the global financial markets (Financial Stability Board, 2025). However, its scale and complexity also create vulnerabilities that can extend beyond individual firms when actuarial assumptions fail, reserves become inadequate, or systemic shocks emerge.

The traditional actuarial models were designed in a context of relatively stable economies, predictable mortality and morbidity rates, and limited risk concentrations. These models were effective for decades but have proved to be inadequate in the face of recent crises because they were based on deterministic assumptions and formula-based reserve calculations. The industry's inability to absorb shocks and predict them has been exposed in recent years by events like the global financial crisis, the COVID-19 pandemic, low interest rates for long periods, and the increasing prevalence of asset-intensive reinsurance arrangements (Sun, 2025; Fortuna & Szwabiński, 2025).

Insurers, actuaries, and regulators have responded by speeding up the adoption of more advanced modeling techniques. Principle-Based Reserving (PBR) moved life insurance reserving from formula-driven requirements to company-specific, model-based assessments of liability adequacy (National Association of Insurance Commissioners, 2022b; American Academy of Actuaries, 2020). Risk-Based Capital (RBC) frameworks have also been developed to reflect the risk exposures of contemporary insurance undertakings, such as complex investment strategies, derivatives, and affiliated reinsurance arrangements (National Association of Insurance Commissioners, 2025). At the broader supervisory level, regulatory initiatives have increasingly emphasized macroprudential monitoring and entity-level oversight to strengthen financial stability (International Association of Insurance Supervisors, 2019).

Meanwhile, machine learning, stochastic simulation, and advanced analytics are revolutionizing the actuarial profession (Richman, 2021; De Virgilis et al., 2022). These tools help insurers to better model policyholder behaviour, assess tail risk, and perform more extensive stress testing (Meng et al., 2022; Gabrielli et al., 2020). As their adoption increases, they have improved

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DOI-https://doi.org/10.5281/zenodo.21100075

the accuracy and flexibility of actuarial models but also posed challenges in the areas of model risk, model explainability, model governance, and model regulation (Actuarial Standards Board, 2019; Pérez-Cruz et al., 2025).

This review is based on the premise that solvency, reserve levels, and systemic risk are closely linked. These are not independent issues; they are different aspects of the broader problem of keeping the insurance system financially sound and able to fulfill its policyholder and economic stability obligations. The study reviews the extent of the use of advanced actuarial modelling in each of these areas, the institutional and methodological deficiencies that remain, and the need for frameworks that are more representative of the complexity of modern insurance and financial systems.

The study will be focused on the following key research question: What are the impacts of advanced actuarial modelling techniques on the management of solvency, reserve adequacy, and systemic risk in the U.S. insurance and financial system, and what are the gaps in existing modelling frameworks? Supporting questions will explore the development of solvency modelling under RBC and emerging approaches to stress testing, the shift from formula-based reserving to principle-based approaches and the actuarial implications, as well as the use of systemic risk measures in insurance supervision and the extent to which these domains are addressed through integrated rather than siloed frameworks.

The study is relevant for actuarial practitioners, insurance regulators, financial stability researchers and policy makers. It offers a synthesis of advanced modelling techniques and their implications for practitioners. It assesses the strengths and weaknesses of existing frameworks for regulators. For scholars, it adds to the body of knowledge on financial risk management by placing actuarial modelling as a key element of financial stability in the U.S. insurance system.

CONCEPTUAL AND THEORETICAL FRAMEWORK

The analytical framework of this review is based on three interrelated theories: classical ruin theory, structural models of financial default, and institutional risk governance theory. These frameworks lay the conceptual foundation for the use of advanced actuarial modeling in the context of solvency assessment, reserve sufficiency, and systemic risk management.

Lundberg's work in 1903 is the foundation of the mathematical theory of ruin, which is used to evaluate the likelihood that an insurer's surplus will become negative when claims and other obligations exceed available resources (Gaigall & Weber, 2025). The classical Cramér-Lundberg model and its various extensions continue to play a pivotal role in the actuarial solvency analysis (Rangita & Ezrah, 2025). Traditional formulations are based on assumptions like stationary claim distributions and independent risk processes, which are increasingly not valid in the complexity of modern insurance portfolios. Advanced actuarial modelling overcomes these shortcomings by using stochastic economic scenarios, non-Gaussian loss distributions, and multivariate dependency structures that more accurately represent current risk settings (Baumgart et al., 2019; Tuysuz & Pekel, 2019).

The Merton structural model of firm default offers a complementary perspective by linking insurer solvency to asset-liability dynamics. By treating equity as a call option on firm assets, the framework models default probability as a function of asset volatility, leverage, and liability structure (Fortuna & Szwabiński, 2025). Beyond the traditional default analysis, its use has grown to evaluate insurer financial strength and balance-sheet risk. More recent adaptations include stochastic interest rates, credit risk, and dynamic interactions in the balance-sheet, which enable the framework to encompass a wider variety of risks that confront modern insurers (Nazzaro, 2025).

The organizational and regulatory environment in which actuarial models are created and used is captured in the institutional risk governance theory. This view focuses on the fact that the success of actuarial modelling relies not only on the technical sophistication of the model, but also on the governance structures, regulatory incentives, and organizational capacities that influence the development, validation, and decision-making of the model (Actuarial Standards Board, 2019b; American Academy of Actuaries, 2019). The framework is especially applicable to the current regulatory environment of insurance, which requires both technical and governance obligations for insurers and their leaders regarding capital standards, reserving requirements, and supervisory frameworks (Actuarial Standards Board, 2019b).

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Within this theoretical context, three core constructs guide the review. Solvency is the ability of an insurer to meet its financial obligations on a going-concern basis and is usually evaluated by a capital adequacy framework that compares available capital with the modelled risk exposures (National Association of Insurance Commissioners, 2025). The sufficiency of technical provisions set aside to satisfy future policyholder obligations in a variety of expected and adverse scenarios is called reserve adequacy (National Association of Insurance Commissioners, 2022b). Systemic risk refers to the potential for insurer distress, failure, or collective market behaviour to disrupt the stability of the broader financial system (Sun, 2025; Das & Fasen-Hartmann, 2025).

These constructs are closely interconnected. Unrecognized liability shortfalls due to reserve inadequacy can erode solvency, and widespread deterioration in solvency can lead to contagion effects that can lead to systemic instability. Likewise, a decline in asset values, changes in interest rates, and credit market disruptions can all impact capital adequacy and reserve sufficiency at the same time. Advanced actuarial modelling is thus more than just a technical tool or activity; it is an institutional process for understanding and managing the relationship between financial uncertainty and financial stability.

Classical actuarial theory continues to be the basis of the contemporary solvency and reserving models. Ruin theory and collective risk models view insolvency as a random event, rather than a binary regulatory event, and offer a framework for assessing financial resilience (Gaigall & Weber, 2025; Rangita & Ezrah, 2025). But today's insurers are confronted by an environment in which the interactions between assets and liabilities are complex, reinsurance arrangements are changing, underwriting practices are developing, and there are macroeconomic influences beyond the scope of traditional surplus models (Ernst & Young, 2025; Fridman & Sayre, 2025).

The structural default framework expands this perspective by linking solvency to market conditions, leverage, and balance-sheet performance. The principle-based approaches build on these concepts by enabling capital and reserve assessments to be based on company-specific risks and scenario outcomes, not just on a deterministic basis (Actuarial Standards Board, 2019a; National Association of Insurance Commissioners, 2022b). Together, these theoretical foundations have contributed to the development of actuarial modelling from static formula-based approaches to adaptive, stochastic, and data-driven approaches to risk management and decision-making.

These three theoretical perspectives have been combined into a complementary analytical lens for this review. Ruin theory offers a probabilistic basis for understanding how insurers become insolvent, as a dynamic process that depends on uncertainty, rather than as a static regulatory threshold. The Merton structural model goes further by connecting the solvency assessment to asset-liability dynamics and market conditions, thereby linking the actuarial and financial risk approaches. The theory of institutional risk governance then places both in the organizational and regulatory context in which actuarial models are developed, validated, and applied. They all contribute to the central theme of this review: solvency, reserve adequacy, and systemic risk are not separate technical issues, but are all aspects of financial resilience that need to be addressed in an integrated way, using integrated modelling frameworks and robust institutional oversight.

METHODOLOGY

The study uses an integrative review methodology to examine the role of advanced actuarial modelling in the assessment of solvency, reserve adequacy, and systemic risk management in the U.S. insurance and financial system. The integrative review approach was selected because it allows for the integration of empirical research, theoretical literature, regulatory guidance, and professional practice documents that are pertinent to this multidisciplinary topic. Literature was identified through academic databases, including Google Scholar, SSRN, arXiv, and ResearchGate, as well as publications from key regulatory and professional organizations such as the National Association of Insurance Commissioners (NAIC), Actuarial Standards Board (ASB), American Academy of Actuaries (AAA), International Association of Insurance Supervisors (IAIS), Financial Stability Board (FSB), and New York State Department of Financial Services (NYDFS). Other sources included reputable actuarial and consulting firms such as Milliman and Ernst & Young. The search terms covered Principle-Based Reserving, Risk-Based Capital, stochastic reserving, Economic Scenario Generators, CoVaR, Marginal Expected Shortfall, machine learning in

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actuarial science, model risk, model governance, AG 53, AG 55, and IAIS Holistic Framework.

Literature was sought using terms individually and in combination across the three main areas of the review. The search focused on publications issued from 2019 to 2025, with earlier seminal works included where necessary to provide theoretical context. Sources that discussed solvency, reserve adequacy, systemic risk modelling, or actuarial applications in insurance and financial risk management were included. Sources that did not contain substantive technical content, were used outside the insurance context, or were not published by academic, regulatory, or professional organizations were not included. The selection of sources included screening of the titles and abstracts, full-text review, and forward and backward citation tracking. The final review comprised 50 sources, including peer-reviewed articles, regulatory publications, actuarial guidance, doctoral research, and industry analyses.

STRENGTHENING SOLVENCY THROUGH ADVANCED ACTUARIAL MODELLING

One of the major issues in actuarial practice and insurance regulation is the solvency of insurers. The evolution of actuarial modelling has turned the concept of solvency evaluation from a static capital-based approach to a dynamic, risk-sensitive approach more suited to the specific risk profile of each individual insurer. The subsequent subsections explore the development of Risk-Based Capital frameworks, the use of stochastic and scenario-based solvency models, and the emerging role of machine learning in solvency assessment.

Risk-Based Capital Frameworks and National Association of Insurance Commissioners (NAIC) Standards

In the early 1990s, the NAIC introduced Risk-Based Capital (RBC) as a departure from minimum capital requirements to risk-based capital standards (National Association of Insurance Commissioners, 2025, February 20). The framework uses a formula to calculate required capital that groups together significant risk categories, such as asset, insurance, interest-rate, and business risks, and includes covariance adjustments for imperfect correlations between the risk categories. An insurer's Total Adjusted Capital is then compared with its Authorized Control Level RBC to determine the appropriate level of regulatory intervention (National Association of Insurance Commissioners, 2025).

While RBC continues to be an essential pillar of U.S. solvency regulation, questions remain about its ability to reflect the full range of risks in the modern insurance business. The formula-based charges might not be commensurate with tail risks that may be inherent in complex investment strategies, affiliated reinsurance arrangements, and long-duration liabilities. Such constraints have become increasingly evident in the expansion of asset-heavy reinsurance deals, where life insurers pass off their long-term obligations to related or foreign reinsurers, while keeping more high-yielding and less liquid assets (Ernst & Young, 2025; Fridman & Sayre, 2025). These types of arrangements pose solvency risks that were not fully considered in the original RBC design.

In response, the NAIC has undertaken significant reforms to strengthen the framework. These efforts include changes to investment risk charges in the life RBC formula and new, more rigorous asset adequacy requirements that incorporate cash-flow testing of ceded reinsurance portfolios into the solvency analysis (National Association of Insurance Commissioners, 2025; National Association of Insurance Commissioners, 2022b). Regulatory standards have also broadened to provide more scrutiny of the ownership of insurers, such as when short-term financial gains could be at odds with long-term policyholder responsibilities (Dechert LLP, 2025).

These developments reflect a broader evolution in regulatory philosophy. Solvency supervision is now focusing more than ever on institution-specific risk assessment with the help of advanced actuarial analysis, instead of treating capital adequacy as a compliance threshold. RBC is useful because it allows regulators to identify potentially undercapitalized insurers and intervene before they reach a tipping point of financial distress (National Association of Insurance Commissioners, 2025). Meanwhile, the continuous reforms acknowledge that the solvency frameworks need to be responsive to emerging risks, changing portfolio structures, and changing market conditions (Sullivan & Cromwell LLP, 2024).

For actuarial practice, the implication is clear: RBC can no longer function solely as a mechanical capital metric. Improved effectiveness can be realized using advanced modelling, which can capture risk dependencies, tail events, and

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exposures that are non-linear and that standardized factor-based approaches may not capture. But the complexity of the model means that robust model validation, transparent documentation, effective model governance, and model interpretability are required (Actuarial Standards Board, 2019b; American Academy of Actuaries, 2019).

Stochastic and Scenario-Based Solvency Modelling

Stochastic modelling has become an integral part of the solvency assessment process because it allows actuaries to assess a set of possible outcomes instead of a single point estimate of capital adequacy (Baumgart et al., 2019; Rangita & Ezrah, 2025). Economic Scenario Generators (ESGs) can be used to aid in this process by generating projections of interest rates, equity returns, credit spreads, and other market variables that can be used as inputs for solvency analysis, especially for life insurance and annuity products (National Association of Insurance Commissioners, Life Actuarial (A) Task Force, 2024). The design and calibration of ESGs have come under increasing regulatory scrutiny, particularly regarding their ability to reflect extreme interest-rate activity (National Association of Insurance Commissioners, Life Actuarial (A) Task Force, 2024). This emphasis is consistent with life insurers' sensitivity to changing rate environments, given the prolonged low-interest-rate environment of the 2010s and the subsequent rapid rate increases (American Academy of Actuaries, 2023).

Scenario-based stress testing has likewise become an important supervisory tool. The exercises call on insurers to evaluate the impact of adverse conditions on their balance sheets, capital positions, and liquidity (International Association of Insurance Supervisors, 2019). Common scenarios include simultaneous declines in asset values, interest-rate shocks, and elevated policyholder surrender activity (National Association of Insurance Commissioners, 2025, August 13). Regulatory obligations for cash-flow testing and multi-scenario reserve analysis further confirm the need to use forward-looking solvency assessments that consider changing economic conditions (New York State Department of Financial Services, 2025b; New York State Department of Financial Services, 2025a).

Stochastic models assess solvency over a range of economic and insurance scenarios, whereas deterministic capital tests do not. This can be especially useful when the capital adequacy is dependent upon the interaction between investment performance, liability behaviour, and underwriting results. Stochastic methods offer a more holistic financial resilience view by modelling distributions of possible outcomes, rather than a single forecast (Tuysuz & Pekel, 2019; Ramos-Pérez et al., 2020).

In practice, these models can incorporate interest-rate movements, equity market shocks, catastrophe losses, lapse behaviour, and reserve deterioration within a unified analytical framework (Mayr, 2025). The effectiveness of these, however, relies on the quality of underlying assumptions and the ability to capture extreme events and risk dependencies accurately. Consequently, calibration of the model, design of scenarios, and sensitivity analysis continue to be critical elements of a credible solvency assessment (Actuarial Standards Board, 2019b).

Applications of Machine Learning in Solvency Analysis

Machine learning analysis of insurance solvency has helped enhance the ability of actuaries to identify complex risk patterns that would not otherwise have been identified using conventional solvency techniques (Richman, 2021; De Virgilis et al., 2022). Such applications have included insurer financial distress prediction, portfolio risk exposure analysis, reinsurance evaluation, as well as identification of any changes to underwriting performance, claims experience, lapse, catastrophe exposure, and reserve development which may impact future capital adequacy (Meng et al., 2022; Opoku et al., 2025). The greatest usefulness of machine learning is its capacity to detect emerging risks and thus enable the deployment of early warning systems.

In practice, machine learning models are used in conjunction with traditional solvency frameworks and are not used independently. In Risk-Based Capital (RBC) frameworks, machine learning approaches have been used to improve the machine learning estimation of component risk factors by accounting for nonlinear relationships among the historical loss and exposure data, observed that are not accounted for in deterministic RBC frameworks (Richman, 2021; De Virgilis et al., 2022). Within stochastic capital models, machine learning has been used to accelerate scenario generation and improve the calibration of tail-risk distributions, enabling more computationally efficient estimates of capital

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adequacy at required confidence levels (De Virgilis et al., 2022; Richman, 2021). But because model opacity and overfitting issues, and limited ability to work well in variable environments can arise, machine learning should be used in conjunction with the existing frameworks, and its use should be in line with the documentation, validation, and professional judgment standards of the applicable actuarial standards of practice (Oyeyemi et al., 2025; Actuarial Standards Board, 2019b).

RESERVE ADEQUACY: APPROACHES, TECHNIQUES, AND ISSUES

Reserve adequacy is concerned with the ability of insurers' reserves to satisfy their future obligations to their policyholders. In recent years, due to various regulatory and actuarial advancements, the process of reserve assessment has moved away from formula-driven models to modeling approaches which place more weight on individual risks faced by the insurers involved.

Statutory vs. Principle-Based Reserving

Prior to Principle-Based Reserving (PBR), statutory reserves for life insurance products were determined using statutory mortality tables, interest rates, and methods of valuation (American Academy of Actuaries, 2020). While this method ensured uniformity, it was prone to producing reserves that did not adequately consider the unique risk experience of individual insurers, leading to either redundancy or insufficiencies depending on the product.

Principle-Based Reserving has been adopted as an alternative that utilizes a combination of formulae and models in determining reserves (Actuarial Standards Board, 2019a). According to VM-20 regulations, insurers maintain the largest of the three: Net Premium Reserve (NPR), Deterministic Reserve (DR), and Stochastic Reserve (SR) (National Association of Insurance Commissioners, 2022b; American Academy of Actuaries, 2020; Actuarial Standards Board, 2019a). Whereas the former provides the reserve floor, the latter two factor in assumptions about the insurer's unique mortality rates, lapse ratios, and expected investment results (National Association of Insurance Commissioners, Life Actuarial (A) Task Force, 2024). Studies show that the NPR is usually the predominant one among the three and, therefore, could be greater than the modelled reserve (American Academy of Actuaries, 2023).

The application of Principle-Based Reserving to annuities via VM-22 has added technical challenges, such as the handling of Interest Maintenance Reserves in the calculation of stochastic reserves (Milliman, 2024). New developments in regulatory requirements have further moved towards assessing the adequacy of reinsurance collateral via principle-based methods (National Association of Insurance Commissioners, 2025, August 13; Fridman & Sayre, 2025).

The primary contribution of PBR is its ability to align reserves more closely with the risk characteristics of individual portfolios. At the same time, reserve adequacy increasingly depends on the quality of assumptions, scenario design, and actuarial judgment used in the modelling process (Actuarial Standards Board, 2019b).

Stochastic Reserving Techniques

Stochastic reserving methods provide an estimate of a range of reserve outcomes, rather than a single reserve value, enabling actuaries to assess the uncertainty in reserves based on different assumptions and scenarios (Tuysuz & Pekel, 2019). Traditional run-off triangle techniques have been extended in non-life insurance by using generalized linear models, state space models, and Bayesian methods to provide statistical inference on reserve development patterns and reserve risk (Ramos-Pérez et al., 2020; Al-Mudafer et al., 2022).

Recent developments include neural networks, deep learning models, and ensemble methods that have been developed to reflect complex claims-development patterns and enhance reserve estimates in volatile or evolving environments (Kuo, 2019; Gabrielli et al., 2020). Reserving analysis can also be extended to include uncertainty in model structure and parameter estimates using Bayesian deep learning methods (Al-Mudafer et al., 2022; Mayr, 2025).

Stochastic reserving is increasingly used in conjunction with Economic Scenario Generators to assess reserve adequacy over a range of interest-rate, equity-market, and credit scenarios in life insurance (National Association of Insurance Commissioners, Life Actuarial (A) Task Force, 2024; American Academy of Actuaries, 2022). Regulatory requirements for multi-scenario cash-flow testing have reinforced the practical application of these techniques in reserve assessment (New York State Department of

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Financial Services, 2025b; New York State Department of Financial Services, 2025a).

The key benefit of stochastic reserving is the ability to estimate the uncertainty of reserves. In addition to the estimation of expected reserves, it offers information on adverse events that could impact capital requirements, reinsurance decisions, and financial planning (Nazzaro, 2025). This is particularly important for long-tailed liabilities, where reserve risk evolves as claims emerge and economic conditions change (Gaigall & Weber, 2025).

AI and Predictive Analytics in Reserve Estimation

AI and predictive analytics are revolutionizing the process of reserve estimation by uncovering patterns in claims development, policyholder behavior, and economic trends that traditional actuarial methods might not capture (Richman, 2021; Gabrielli et al., 2020). The adoption of digital claims management, real-time claim data collection, and IoT (Internet of Things) monitoring has led to a surge in the amount and the timeliness of information that insurers have access to when analysing reserves, enabling them to respond more quickly to new liability trends (Anim-Sampong & Oman-Amoako, 2026; Okeke et al., 2025).

These tools are particularly valuable in personal lines, health-related coverages, and other high-volume claims environments, where they can detect claim-development anomalies, segmentation effects, and complex behavioural patterns (Kuo, 2019; Meng et al., 2022). These insights help to build better assumptions and to monitor the emergence of reserves more effectively. Insurers with investments in advanced analytics have increasingly leveraged these capabilities to enhance the accuracy of reserves and minimize the need for conservative reserve margins (De Virgilis et al., 2022). This change is also in line with the rising demand that reserve assumptions be based on the experience of the company in question, not the industry (Actuarial Standards Board, 2019b).

Predictive accuracy, however, does not guarantee reserve adequacy. Models derived from past data can become unreliable if there is a change in claims behavior, inflation, or economic conditions (Agbadamasi et al., 2025; Brakye & Yeboah, 2026). These issues of model stability, auditability, and overfitting are thus still relevant (Pérez-Cruz et al., 2025; Lindholm et al., 2022; Clement & Colley, 2026). In this regard, AI is best suited to augment and complement actuarial analysis and monitoring of reserves, and to assist in the evaluation of future liabilities, not to replace actuarial judgment (American Academy of Actuaries, 2019).

Model Risk and Validation in Reserving

A major difficulty in reserving is the model risk involved, as estimates of reserves are based on assumptions about mortality, lapse behavior, claims severity, inflation, discounting, and tail outcomes (American Academy of Actuaries, 2019; Actuarial Standards Board, 2019b). The use of Principle-Based Reserving has resulted in a greater use of company-specific assumptions, economic scenario generators, and adverse-deviation margins, which increases the opportunities for error in model specification and calibration (Actuarial Standards Board, 2019b; National Association of Insurance Commissioners, 2022b).

Recent regulatory reviews have highlighted these challenges, particularly in the valuation of long-term liabilities supported by asset-intensive reinsurance arrangements (National Association of Insurance Commissioners, 2022a; National Association of Insurance Commissioners, 2025). For traditional cash-flow testing and reserve assessment, complex asset structures such as payment-in-kind instruments and tiered tranches can pose difficulties (Ernst & Young, 2025; Fridman & Sayre, 2025).

To mitigate these risks, validation frameworks have been developed that include sensitivity analysis, parameter stability testing, back-testing when possible, and data quality and structural change assessment (American Academy of Actuaries, 2019; Actuarial Standards Board, 2019b, December; Yeboah et al., 2026; Yirenkyi, 2026). Even if the underlying model is sound, reserve models can become unreliable due to changes in underlying portfolio characteristics, claims patterns, or economic factors (Mayr, 2025; Ramos-Pérez et al., 2020). Recent actuarial research has also developed quantitative methods for assessing the impact of individual assumptions on reserve uncertainty, which enables actuaries to identify sources of model risk and to make more informed decisions regarding reserve adequacy and reserve margins (Actuarial Standards Board, 2019b; American Academy of Actuaries, 2022).

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SYSTEMIC RISK MODELING IN U.S. INSURANCE AND FINANCIAL SYSTEMS

American International Group's near failure in 2008 underscored the possibility of a large insurance group to spread financial distress beyond the insurance industry. The systemic risk modeling has since grown to incorporate entity-level risk measures, network-based contagion models, and macroprudential supervisory tools that seek to identify and deal with vulnerabilities at the macro level. The main measures adopted to evaluate systemic risk in insurance are explored in the following subsections, as well as the mechanisms that give rise to interconnectedness and contagion, and the regulatory measures put in place to tackle these risks.

Systemic Risk Measures: CoVaR, MES, and SES

Tools originally developed in the banking sector have been adapted to measure systemic risk in insurance. CoVaR assesses the level of financial-system risk conditional on an individual institution being in distress, while Marginal Expected Shortfall (MES) and Systemic Expected Shortfall (SES) estimate an institution's expected losses during systemic events and its contribution to system-wide capital shortfalls (Leeuwenkamp, 2022; Sun, 2025). These measures offer a framework to assess the potential for insurer distress to impact financial stability more broadly. Recent research has extended these measures to insurance-specific settings, particularly where risk exposures are linked through common asset holdings, reinsurance networks, and shared macroeconomic conditions (Das & Fasen-Hartmann, 2025; Chen et al., 2025).

Studies on dependence uncertainty have revealed the challenges in quantifying systemic exposure when the relationships between risks are not completely known (Chen et al., 2025). The current systemic vulnerabilities assessment lists interest-rate risk, liquidity risk, surrender risk, funding risk, and credit risk as concerns, in addition to the increasing proportion of hard-to-value assets in insurer portfolios (Financial Stability Board, 2025). Theoretical foundations of systemic risk measurement in insurance have also been enhanced by methodological advances. Multi-dimensional renewal models with heterogeneous claims and multiple business lines enable the assessment of solvency results and systemic risk contributions of diversified insurance portfolios simultaneously (Gaigall & Weber, 2025). These methods are more reflective of the operational complexity of large insurance groups and offer a more holistic perspective on the potential for risks to build up and interact between business segments.

Despite their usefulness, CoVaR, MES, and SES have limitations. Their findings can be sensitive to the model assumptions and can fail to robustly identify systemically important institutions (Leeuwenkamp, 2022; Fortuna & Szwabiński, 2025). To insurers, they are more a screening tool to highlight potential vulnerabilities, not definitive measures of systemic importance. Insurance-related systemic risk extends beyond market-based tail dependence to include asset-liability mismatches, reinsurance structures, and long-duration policy obligations (Sun, 2025).

Interconnectedness and Contagion in Insurance Markets

Insurers can pass financial distress on via their liability structures and investment portfolios. Correlated policyholder behavior, including elevated surrender activity during periods of stress, can create simultaneous liquidity demands across multiple firms (Sun, 2025). Meanwhile, the transmission of shocks via asset price changes and losses in portfolio holdings can occur from common exposures to government bonds, corporate bonds, and alternative assets (Das & Fasen-Hartmann, 2025; Fortuna & Szwabiński, 2025).

Asset-intensive reinsurance has added another layer of interconnectedness by linking U.S. insurers to offshore and affiliated reinsurers through long-duration liability transfers (Ernst & Young, 2025; Fridman & Sayre, 2025). The release of reserves, asset quality, liquidity, and credit risk have been a concern, leading to increased regulatory oversight and asset adequacy requirements (National Association of Insurance Commissioners, 2025; National Association of Insurance Commissioners, 2022a). These advances stress the importance of considering risk at the group level, not at the individual legal entity level.

Network-based models offer a way to understand the dynamics of the spread of distress in the context of reinsurance relationships, common asset holdings, counterparty exposures, and group structures. Traditional risk models are extended by incorporating interactions between the components of a portfolio and between interconnected entities

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through recent methodological developments such as jointly exchangeable collective risk models. These approaches offer a more realistic representation of contagion pathways and systemic vulnerability within complex insurance networks (Das & Fasen-Hartmann, 2025).

Regulatory Responses: FSOC, IAIS, and Stress Testing Frameworks

Since the establishment of FSOC under the Dodd-Frank Act, the insurance sector's regulatory structure for systemic risk has changed significantly. The designation and later de-designation of key insurance companies as systemically important financial institutions (SIFIs) continued to be a subject of debate as to whether traditional insurance activities create the same liquidity and interconnectedness risks as banking (Sun, 2025; Buabin & Adegoke, 2025).

Internationally, the IAIS replaced the identification of globally systemically important insurers with its Holistic Framework, which combines entity-level supervision, macroprudential measures, and sector-wide monitoring through the Global Monitoring Exercise (GME) (International Association of Insurance Supervisors, 2019). The framework has been adopted as the main international framework for systemic-risk oversight and has been reiterated by the Financial Stability Board as the foundation for its insurance-sector systemic-risk assessment (Financial Stability Board, 2025). The introduction of the Insurance Capital Standard (ICS) as a prescribed capital requirement for internationally active insurance groups added to the drive towards a globally consistent capital framework in parallel with national capital regimes (Sullivan & Cromwell LLP, 2024).

Stress testing plays a central role in this supervisory structure. At the firm level, Own Risk and Solvency Assessments (ORSA) assess insurer resilience under adverse conditions, and the GME assesses the accumulation of vulnerabilities across the wider insurance sector (International Association of Insurance Supervisors, 2019). The GME methodology has been revised recently, incorporating updates to insurer selection criteria, Level 3 asset indicators and assessment weights, in response to the changing sources of systemic risk and market conditions (Financial Stability Board, 2025).

One of the ongoing issues is the integration of solvency, reserving, and systemic-risk oversight. These functions are frequently subject to distinct regulatory regimes, reporting requirements and supervision. More integrated approaches that connect firm-level solvency measures with stress testing and contagion analysis could provide a more comprehensive view of risk across the insurance system.

DISCUSSION

The evidence examined suggests that there is significant advancement in the use of advanced actuarial modelling for solvency assessment, reserve adequacy and systemic risk monitoring. The industry's capacity to measure risk in a changing environment has been enhanced by developments such as Principle-Based Reserving, improved capital frameworks, stress testing, and systemic-risk surveillance (National Association of Insurance Commissioners, 2022b; International Association of Insurance Supervisors, 2019). Concurrently, there are ongoing issues of model integration, regulatory coordination, and dealing with emerging risks.

One of the main results is the interdependence between solvency, the adequacy of reserves, and systemic risk. Reserve deficiencies can weaken reported capital positions, while weaknesses in capital adequacy increase vulnerability to broader financial stress. The review indicates that this interaction is well demonstrated in asset-intensive reinsurance. Complex liability transfer mechanisms can appear to present reserve strength but also carry risks that are not necessarily reflected in the traditional approach to solvency (Ernst & Young, 2025; Fridman & Sayre, 2025). Likewise, interconnected reinsurance arrangements and common asset exposures create channels through which firm-level weaknesses can evolve into broader systemic concerns.

The review also identifies opportunities and challenges in increasingly data-intensive modeling approaches. While machine learning and predictive analytics have enhanced risk classification, pattern detection, and reserve estimation (Richman, 2021; De Virgilis et al., 2022), there are concerns about model transparency and reliability (Pérez-Cruz et al., 2025; Actuarial Standards Board, 2019b). Models that have been successful in the past may not be as effective when market conditions, policyholder behavior, or claim patterns shift. Therefore, even with more sophisticated models, critical evaluation of model outputs and underlying assumptions is

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still required (American Academy of Actuaries, 2019).

One of the constant themes is the disintegration of the existing modeling environment. The development of solvency models, reserving models, and systemic-risk frameworks is frequently done independently, but with many of the same assumptions, stress scenarios, and asset-liability relationships. This disconnection can mask risks that arise in several areas. The development of fully integrated modelling approaches is still incomplete, while Enterprise Risk Management frameworks and Own Risk and Solvency Assessments (ORSA) are attempts to link these functions (International Association of Insurance Supervisors, 2019; American Academy of Actuaries, 2022).

The review further identifies an ongoing tension between regulatory consistency and jurisdictional flexibility. While state-based regulation promotes innovation and supervisory discretion, there may be variation in risk assessment and actuarial standards because of the differences in oversight practices (Dechert LLP, 2025). At the same time, international initiatives such as the Insurance Capital Standard introduce additional layers of capital oversight that must operate alongside existing U.S. frameworks (Sullivan & Cromwell LLP, 2024).

Lastly, the insurance industry is undergoing structural transformation, which is impacting the context in which actuarial models operate. The development of asset-intensive reinsurance, increasing exposure to illiquid assets, the development of annuity markets, and the changing ownership structures have brought about risks that span solvency, reserving, and systemic-risk issues (National Association of Insurance Commissioners, 2025, August 13; Financial Stability Board, 2025). These developments reinforce the need for modelling frameworks capable of capturing interactions among assets, liabilities, capital positions, and contagion channels without relying on isolated assessments of risk.

RECOMMENDATIONS

The results of this review support several recommendations to improve actuarial modelling and risk oversight in the U.S. insurance industry.

First, regulators and insurers should prioritize integrated modelling frameworks that treat solvency, reserve adequacy, and systemic risk as interconnected components of enterprise risk management. To enhance the consistency of risk assessments, capital models, reserving models, and stress-testing frameworks should be built on common assumptions, scenario libraries, and validation standards. Existing ORSA frameworks provide a foundation for this integration and should be strengthened through greater emphasis on integrated stress testing, scenario analysis, and balance-sheet modelling.

Second, the NAIC and state insurance regulators should establish more consistent standards for the use of AI and machine learning in actuarial applications. Across jurisdictions, minimum requirements for model documentation, validation, transparency and accountability should be applied to minimize regulatory inconsistencies and opportunities for regulatory arbitrage. These standards would enable the responsible use of advanced analytics, while maintaining actuarial accountability.

Third, the ongoing development of capital and reserving standards should be paired with more investment in actuarial skills in state insurance departments. Regulators will need to be able to effectively assess model assumptions, question model outputs, and effectively identify emerging risks as the complexity of solvency and reserving models increases.

Fourth, the actuarial profession should enhance insurance-specific methods for measuring systemic risk. Although indicators such as CoVaR, MES and SES are useful, they should be integrated with indicators that reflect reinsurance interconnectedness, long-duration liabilities, common asset exposures, and balance-sheet vulnerabilities. Matching these measures to the broader supervisory monitoring frameworks would enhance firm-level risk management and macroprudential oversight.

Fifth, machine learning, network analysis, integrated risk modeling, model risk assessment, and systemic-risk measurement should be emphasized in actuarial education and professional development. Expanding these competencies will better prepare future practitioners for an increasingly data-intensive and interconnected risk environment.

Lastly, firms should leverage machine learning as a tool to support forecasting, monitoring, and decision-making, not replace actuarial analysis and statutory compliance. Advanced analytical

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methods work best when used in conjunction with good actuarial judgment, sensitivity analysis, appropriate documentation of method limitations, and an understanding of where expert judgment influences the model results.

CONCLUSION

This review examined the role of advanced actuarial modelling in strengthening solvency assessment, reserve adequacy, and systemic risk management within the U.S. insurance and financial system. The evidence shows that the industry has become more capable in managing risk in a more complex environment, due to developments like Principle-Based Reserving, improved capital frameworks, stochastic modelling, and systemic-risk monitoring.

At the same time, the review highlights a persistent challenge: solvency, reserving, and systemic risk are often modelled and supervised separately despite their close interdependence. Weaknesses in one area can impact the others, as demonstrated by asset-intensive reinsurance, interconnected insurance networks, and the broader structural changes in the insurance sector. Therefore, the future success of actuarial practice will rely not only on further development of actuarial modelling but also on the increased integration across risk-management and supervisory frameworks.

Advanced actuarial models should be transparent enough for effective oversight, flexible enough to capture new risks, and robust enough to withstand stress to ensure financial resilience. In a sector that plays a critical role in financial stability, the value of actuarial modelling ultimately depends on its ability to provide a coherent view of risk across reserves, capital, and systemic exposures.

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Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:

Awotwe, E. & Oman-Amoako, M. "Advanced Actuarial Modelling in U.S. Insurance and Financial Systems: Strengthening Solvency, Reserve Adequacy, and Systemic Risk Management." *Journal of Economics Intelligence and Technology* 2.2 (2026): pp 1-13.

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