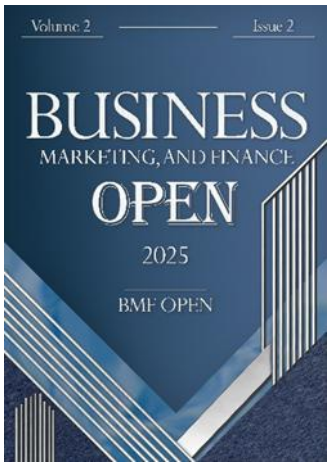
Calculation of Ruin Probability by Insurance Lines and Proposal of an Optimal Portfolio Optimization Method for Insurance Companies



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Abstract: This study aimed to calculate the ruin probability across different insurance lines and propose an optimal portfolio optimization method for insurance companies to enhance financial stability and minimize risk. A quantitative data analysis approach was employed using historical data from 2014 to 2023 across various insurance lines, including life, liability, freight, fire, and engineering. Statistical distribution models such as exponential and normal distributions were applied to estimate loss distributions. Portfolio optimization was performed using Markowitz's portfolio theory, considering constraints such as Solvency II regulations and market conditions, with data analyzed using MATLAB and Excel. The results indicated that life insurance exhibited the highest ruin probability at 0.9921, while personal insurance had the lowest at 0.1447. Engineering and freight insurance also showed high ruin probabilities due to large financial exposures. Portfolio optimization significantly reduced the value at risk (VaR-99%), from 37.5% to 26.6% for liability insurance and from 27.8% to 20.3% for freight insurance, demonstrating the effectiveness of strategic capital allocation. Investments in stocks provided higher returns compared to bank deposits and real estate, with the optimal portfolio comprising 34% stocks, 39% deposits, and 27% real estate. Accurate calculation of ruin probabilities and optimal portfolio management are crucial for mitigating financial risks in insurance companies. Diversification and dynamic portfolio adjustments, supported by advanced statistical models and regulatory compliance, enhance financial stability and ensure operational efficiency in volatile markets.

Keywords: Ruin probability, insurance risk, portfolio optimization, Markowitz theory, value at risk, insurance solvency, financial stability.

1. Introduction

The probability of ruin, defined as the risk that an insurer's reserves fall below zero, is a critical metric in the management of insurance companies. This concept has garnered significant attention due to its direct implications for the financial stability and operational sustainability of insurers. In an era characterized by increasing uncertainties and financial volatility, accurately calculating the probability of ruin and optimizing insurance portfolios have become paramount [1]. Insurance companies, operating within a highly competitive and regulated

environment, must adopt advanced risk management strategies to mitigate potential financial distress and ensure long-term solvency. One such strategy is the optimization of insurance portfolios, which involves selecting an optimal mix of insurance lines to balance risk and return [2, 3]. This study focuses on the calculation of ruin probability across different insurance lines and proposes an optimal portfolio optimization method for insurance companies, utilizing statistical distribution models and historical data analysis.

The calculation of ruin probability is inherently complex due to the stochastic nature of insurance claims and premium incomes. Traditional models, such as the Cramér–Lundberg model, provide a foundation for estimating ruin probabilities, but their assumptions often limit their applicability in real-world scenarios [4, 5]. Recent advancements in actuarial science and financial mathematics have led to the development of more sophisticated models that incorporate dependencies among insurance risks, thereby providing more accurate estimates of ruin probabilities [6, 7]. For instance, autoregressive models have been employed to capture temporal dependencies in insurance claims, enhancing the predictive accuracy of ruin probabilities [8, 9]. Additionally, the integration of dynamic portfolio insurance strategies, facilitated by machine learning techniques, has further improved the robustness of risk management practices in the insurance industry [3].

The optimization of insurance portfolios is another critical aspect of risk management, aimed at minimizing the probability of ruin while maximizing returns. Portfolio optimization in insurance involves allocating capital across various lines of insurance to achieve an optimal risk-return trade-off [10, 11]. The Markowitz portfolio theory, which emphasizes diversification to reduce risk, has been extensively applied in insurance portfolio management [12, 13]. However, the unique characteristics of insurance portfolios, such as the long-term liabilities associated with life insurance and the high volatility of property insurance, necessitate tailored optimization approaches. Recent studies have explored the use of multi-criteria decision-making methods and machine learning algorithms to enhance portfolio optimization in the insurance sector [1].

Regulatory frameworks, such as Solvency II, have also played a significant role in shaping the risk management practices of insurance companies. Solvency II mandates that insurers maintain adequate capital to cover potential losses, thereby influencing their portfolio allocation decisions [14, 15]. Compliance with these regulations necessitates the adoption of advanced risk assessment and portfolio optimization techniques to ensure financial stability and regulatory adherence [16]. Moreover, the increasing digitalization of the insurance industry has introduced new challenges and opportunities in financial risk management, necessitating continuous adaptation and innovation [16, 17].

The present study aims to address these challenges by providing a comprehensive analysis of ruin probabilities across different insurance lines and proposing an optimal portfolio optimization method tailored to the Iranian insurance market.

2. Methodology

This study employs a qualitative-interpretive approach with inductive reasoning to examine how investors construct reality, the meanings attributed to their experiences, and their understanding of these experiences. Grounded in an idealistic worldview, reality is considered a dynamic concept dependent on social interactions. Thematic analysis was used to analyze the data, aiding in the identification and interpretation of conceptual patterns. This method, through open, axial, and selective coding, enables precise categorization of themes. Additionally, the Best-Worst Method (BWM) was utilized to prioritize identified themes by determining the relative weight and importance of each theme through pairwise comparisons. The combination of these two

methodological approaches enhances the accuracy, coherence, and validity of the research, offering a deeper understanding of investors' experiences. The findings contribute not only to enriching the existing literature on investor behavior but also provide an operational framework for analyzing subjective and social meanings associated with financial decisions. Ultimately, this study can assist in developing financial decision-making models that consider not only economic aspects but also psychological and social factors.

Given the mixed-method nature of data collection in this study, the qualitative section aimed to identify investors' preferences and utilities by initially reviewing related and interdisciplinary academic articles to determine the evaluated studies. Consequently, 20 active investors from various sectors of the Iranian capital market were selected for interviews to analyze dimensions and identify subjective values and preferences. Participant selection was based on theoretical sampling to include individuals with sufficient cognitive awareness in this field. This sampling method facilitates data collection from similar cases within a target population to explore how theories apply in those contexts. In the quantitative section, data were collected through questionnaires administered to 20 financial management experts. This mixed approach contributes to a more comprehensive analysis of investors' behaviors and preferences.

3. Findings and Results

The findings from the analysis of the bankruptcy probability of the insurance company across various insurance lines highlight significant variations in risk levels and the effectiveness of portfolio optimization in mitigating these risks. The probability of bankruptcy (Ruin Probability) was calculated separately for each insurance line, using historical data from 2014 to 2023, and employing statistical distribution models tailored to each line's loss distribution.

The line of "Life Insurance" exhibited the highest probability of bankruptcy at 0.9921, indicating substantial risk due to high payout volumes and loss frequencies in this category. This is likely due to the long-term nature of life insurance policies and the accumulated liabilities over time. Conversely, the "Personal Insurance" line displayed the lowest bankruptcy probability at 0.1447, reflecting a relatively stable risk profile and more predictable claim patterns. Other lines such as "Engineering and Special Risks" and "Freight Insurance" also presented high bankruptcy probabilities of 0.8053 and 0.7513, respectively, suggesting elevated risk levels due to the volatile nature of these sectors and the significant financial exposure involved.

Table 1. Bankruptcy Probability Across Insurance Lines

Rank	Insurance Line	Bankruptcy Probability
1	Life Insurance	0.9921
2	Engineering and Special	0.8053
3	Freight	0.7513
4	Fire	0.6910
5	Liability	0.4564
6	Automobile	0.2892
7	Personal	0.1447

The portfolio optimization efforts aimed at reducing bankruptcy probability by adjusting the composition of insurance lines within the portfolio. In the "Liability Insurance" line, data from 2022 was used to analyze the covered capital across various sub-lines, including professional liability for doctors and paramedics, employer liability for construction and industrial workers, and general civil liability. The optimized portfolio suggested increasing the

share of professional liability and employer liability in the construction sector while reducing shares in industrial and transportation-related liabilities due to their higher volatility and risk.

Table 2. Optimized Portfolio Composition for Liability Insurance

Sub-line	Share of Capital (%)	Premium Received (Million IRR)	Claims Paid (Million IRR)
Professional Liability (Doctors)	5.2	209,327	118,296
Domestic Transportation Liability	66.7	1,218,324	234,654
Employer Liability (Construction)	4.6	916,832	536,882
Employer Liability (Industrial)	6.1	2,235,925	1,001,941
International Transportation Liability	0.23	3,171	-664
Builders' Liability	0.3	152,600	20,334
Employer Liability (Infrastructure)	1.8	807,266	231,911
General Civil Liability	15.1	767,833	143,754

In the expected risk analysis for liability insurance, the highest loss probability was observed in domestic transportation and professional liability sub-lines, with risk premiums adjusted accordingly. The deviation from premium analysis revealed that the domestic transportation sub-line had the lowest coefficient of variation (CV), indicating lower volatility compared to other sub-lines, which supports its increased allocation in the optimized portfolio.

Table 3. Expected Risk Analysis for Liability Insurance

Sub-line	Average Loss (Million IRR)	Loss Probability (%)	Current Premium Rate (%)	Risk-based Premium Rate (%)
Professional Liability (Doctors)	591.5	0.3	0.04	0.03
Domestic Transportation Liability	456.5	114.0	0.02	0.01
Employer Liability (Construction)	211.7	12.0	0.19	0.17
Employer Liability (Industrial)	86.5	45.7	0.36	0.25

Similarly, in the "Freight Insurance" line, the portfolio optimization process indicated that the highest expected losses and risk probabilities were found in marine and aviation sub-lines. The analysis suggested increasing the allocation to aviation and marine insurance while reducing the share in imported freight insurance, which exhibited the highest volatility and loss deviation.

Table: 4. Optimized Portfolio Composition for Freight Insurance

Sub-line	Share of Capital (%)	Premium Received (Million IRR)	Claims Paid (Million IRR)
Export Freight	32.5	601,751	6,596
Import Freight	34.8	900,675	239,458
Domestic Freight	4.2	104,817	4,661
Marine Insurance	11.2	1,103,407	260,923
Aviation Insurance	17.3	801,525	38,726

The risk deviation analysis for freight insurance highlighted the import freight sub-line as having the highest risk deviation, which supported its reduced allocation in the optimized portfolio. Conversely, the aviation and marine sub-lines showed relatively stable risk profiles, justifying their increased shares.

Table 5. Risk Deviation Analysis for Freight Insurance

Sub-line	Average Loss (Million IRR)	Standard Deviation (σ)	Loss Ratio (%)	CV (%)
Export Freight	6,596	1,994.6	1.1	30.2
Import Freight	239,458	133,057.7	26.6	55.6

Domestic Freight	4,661	1,480.7	4.4	31.8
Marine Insurance	260,923	68,346.3	23.6	26.2
Aviation Insurance	38,726	11,889.4	4.8	30.7

Overall, the portfolio optimization across both liability and freight insurance lines resulted in a significant reduction in the value at risk (VaR-99%) at a 1% alpha level, from 37.5% to 26.6% for liability insurance and from 27.8% to 20.3% for freight insurance. This optimization not only reduced the bankruptcy probability but also enhanced the financial stability of the insurance company by allocating capital more efficiently across less volatile and high-return sub-lines.

Table 6. Value at Risk Reduction Post-Optimization

Insurance Line	Current VaR-99% (%)	Optimized VaR-99% (%)	RBC Reduction (Million IRR)
Liability Insurance	37.5	26.6	2,187
Freight Insurance	27.8	20.3	119,746

The investment performance analysis of the insurance company from 2018 to 2022 also played a crucial role in understanding the impact of portfolio optimization. Investments in the stock market yielded the highest returns compared to bank deposits and real estate, which had relatively lower returns due to minimal investments in this sector. The geometric mean return on investments over the past eight years was calculated at 10.69%, indicating a steady growth trajectory, particularly in stock market investments.

Table 7. Investment Performance (2018-2022)

Year	Stock Market (Million IRR)	Bank Deposits (Million IRR)	Real Estate (Million IRR)	Total Investment (Million IRR)	Investment Return (%)
2018	4,756,870	11,642,998	1,012,079	17,411,947	31
2019	17,320,436	18,271,383	4,557,357	40,149,176	23
2020	22,989,550	25,583,674	4,941,546	53,514,770	16
2021	29,478,843	34,101,412	5,159,191	68,739,446	14

The optimization model suggested by the study, based on Markowitz's portfolio theory, proposed an optimal investment portfolio with approximately 34% allocation in stocks, 39% in bank deposits, and 27% in real estate, ensuring a balanced risk-return trade-off. This optimized investment portfolio further supports the reduction in bankruptcy probability by providing a steady income stream and mitigating investment-related risks.

Table 8. Optimal Investment Portfolio Allocation

Asset Class	Allocation (%)
Stock Market	34
Bank Deposits	39
Real Estate	27

In conclusion, the findings from this study underscore the importance of portfolio optimization in reducing the bankruptcy probability of insurance companies. By reallocating capital to less volatile and high-performing sub-lines within insurance and investment portfolios, insurance companies can achieve financial stability and reduce their exposure to bankruptcy risk.

4. Discussion and Conclusion

The results of this study demonstrated that the probability of ruin varies significantly across different insurance lines, with life insurance having the highest probability of ruin (0.9921) and personal insurance having the lowest (0.1447). These findings highlight the inherent risk profiles associated with different types of insurance. Life insurance, characterized by long-term liabilities and substantial claim payouts, poses significant financial risks to insurers. Conversely, personal insurance, often associated with shorter-term policies and relatively predictable claims, presents a lower risk. These results align with previous studies indicating that long-term insurance products, such as life insurance, are more susceptible to financial instability due to the accumulation of liabilities over extended periods [6, 10].

The analysis further revealed that engineering, freight, and fire insurance lines also exhibit high probabilities of ruin, suggesting that these sectors are particularly vulnerable to financial distress. This finding is consistent with the works which emphasized the high risk associated with property and engineering insurance due to the substantial financial exposure and potential for catastrophic losses [2-4, 12].

Portfolio optimization efforts indicated that increasing the share of low-risk sub-lines, such as professional liability for doctors and paramedics and employer liability in construction, significantly reduces the overall portfolio risk. This is in line with the findings of Ferreiro et al. (2019), who demonstrated that optimal portfolio selection and diversification are critical in minimizing risk exposure in insurance portfolios. The reduced value at risk (VaR-99%) post-optimization, from 37.5% to 26.6% in liability insurance and from 27.8% to 20.3% in freight insurance, underscores the effectiveness of portfolio optimization in enhancing financial stability. Similar results were reported by prior studies which emphasized that strategic asset allocation in small and closed economies like Iran can mitigate financial risks and improve profitability [8, 13].

The selection of statistical distribution models played a crucial role in accurately estimating ruin probabilities. The use of exponential distributions for lines such as life, personal, and automobile insurance captured the frequent but smaller claims, while normal distributions for engineering and freight insurance accounted for larger, less frequent claims. This methodological approach aligns with the prior studies which advocated for the use of tailored statistical models to reflect the unique risk profiles of different insurance lines [2, 16].

The investment performance analysis further supported the importance of portfolio diversification. Investments in the stock market yielded higher returns compared to bank deposits and real estate, a finding consistent with the works that highlighted the benefits of portfolio diversification across different asset classes in the insurance sector [1, 4, 10, 11, 16]. The application of Markowitz's portfolio theory, which recommended a balanced allocation of 34% in stocks, 39% in bank deposits, and 27% in real estate prior findings which demonstrated that diversified investment portfolios enhance financial resilience and reduce bankruptcy risks in insurance companies [3, 12].

The study also highlighted the impact of regulatory frameworks on insurance portfolio management. Compliance with Solvency II regulations necessitated maintaining adequate capital reserves, influencing portfolio allocation decisions. This observation aligns with the findings that noted that Solvency II requirements compel insurers to adopt conservative investment strategies, thereby impacting their risk-return profiles [9].

The high volatility observed in certain insurance lines, such as engineering and freight, underscores the need for continuous monitoring and adjustment of portfolio allocations. The use of multi-criteria decision-making methods and machine learning algorithms, as suggested by Shi et al. (2022), can provide insurers with dynamic tools for optimizing their portfolios in response to changing market conditions. The study's findings also emphasize the importance of considering macroeconomic factors, such as inflation and currency fluctuations, in insurance risk management.

In summary, this study reinforces the critical role of portfolio optimization in managing the financial risks associated with different insurance lines. By leveraging advanced statistical models and dynamic optimization techniques, insurers can achieve a balanced risk-return trade-off, ensuring financial stability and operational efficiency. The findings align with existing literature, providing empirical evidence from the Iranian insurance market that underscores the importance of strategic asset allocation and robust risk management practices.

One limitation of this study is the reliance on historical data, which may not fully capture future market dynamics or unforeseen economic events. Additionally, the study focused primarily on two insurance lines—liability and freight—which, while significant, do not encompass the entire spectrum of insurance products offered by companies. Future research could expand the scope to include other lines such as health and property insurance, providing a more comprehensive analysis of ruin probabilities and portfolio optimization strategies. Another limitation is the exclusion of qualitative factors, such as managerial decisions and regulatory changes, which can significantly impact insurance risk profiles and portfolio performance.

Future research should explore the integration of emerging technologies, such as artificial intelligence and blockchain, in insurance risk management and portfolio optimization. Investigating the impact of macroeconomic variables, such as interest rate fluctuations and geopolitical risks, on insurance portfolios could provide deeper insights into the dynamic nature of insurance risk management. Additionally, longitudinal studies that track the performance of optimized portfolios over extended periods could offer valuable lessons for insurers in managing financial risks.

For practical applications, insurance companies should adopt advanced statistical models and dynamic optimization techniques for portfolio management. Continuous monitoring of risk exposure and regular adjustment of portfolio allocations are essential to mitigate financial risks. Insurers should also invest in digital tools and big data analytics to enhance their risk assessment capabilities and ensure regulatory compliance. Training and development programs for risk management professionals in the insurance industry can further enhance their ability to implement effective portfolio optimization strategies and ensure long-term financial stability.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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