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MINIMAX OPTIMIZATION IN BUSINESS INTELLIGENCE SYSTEMS FOR FINANCIAL DECISION-MAKING UNDER ECONOMIC UNCERTAINTY

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ABSTRACT

In highly volatile economic environments, financial decision-making based on average or expected outcomes becomes increasingly fragile. Business Intelligence (BI) systems, while effective for descriptive and predictive analytics, often lack robust mechanisms to support decision-making under deep economic uncertainty. This study proposes and validates a minimax optimization framework integrated into Business Intelligence systems to enhance financial decision-making robustness under adverse economic scenarios. A quantitative analytical design was employed, grounded in mathematical modeling and robust optimization. Financial decisions were formalized as a minimax optimization problem, where the objective is to maximize the minimum guaranteed financial performance across multiple adverse economic scenarios. The proposed model was integrated into a prescriptive BI architecture and validated through simulated macroeconomic scenarios involving growth, stagnation, recession, and severe crisis conditions. Performance was evaluated using normalized financial indicators, including return, risk exposure, and maximum loss. Results demonstrate that decisions derived from the minimax approach significantly reduce maximum financial losses and exhibit greater stability compared to traditional BI decisions based on expected value optimization. While conventional approaches favored high-average-return strategies with high downside risk, the minimax framework consistently selected robust strategies that ensured superior worst-case performance. The findings confirm that minimax optimization enhances financial resilience and reduces vulnerability to extreme economic shocks. This study contributes theoretically by extending minimax decision theory to Business Intelligence systems and practically by providing a replicable prescriptive BI model for robust financial decision-making under uncertainty. The proposed framework supports the development of more resilient, transparent, and risk-aware financial intelligence systems.

KEYWORDS: Business Intelligence; Minimax Optimization; Financial Decision-Making; Economic Uncertainty; Robust Optimization; Prescriptive Analytics.

1. INTRODUCTION

Context and Background

In an economic environment characterized by high volatility, recurrent crises, and unpredictable external shocks, organizations face increasing challenges in strategic financial decision-making. Factors such as market fluctuations, inflation, geopolitical instability, and regulatory changes significantly increase economic uncertainty, reducing the reliability of traditional financial analysis models based on stability assumptions.

In this context, Business Intelligence (BI) systems have established themselves as key tools for the processing, analysis and visualization of large volumes of financial data, allowing decision-makers to access timely and relevant information. However, most current BI systems prioritize average descriptive and predictive analysis, without explicitly incorporating robust optimization mechanisms against adverse scenarios.

Research Problem

Despite advances in financial analytics and BI, a critical limitation remains: decision support systems often optimize the expected value of financial results, ignoring the impact of worst-case economic scenarios. In contexts of high uncertainty, this approach can lead to suboptimal or even catastrophic decisions, especially in risk-sensitive sectors.

There is, therefore, a methodological and technological gap in the integration of minimax optimization models within business intelligence systems, aimed at guaranteeing financial decisions that maximize the minimum expected profit and minimize exposure to severe losses.

Rationale for the Study

The minimax criterion, widely used in game theory, quantitative finance, and engineering, offers a robust framework for decision-making under extreme uncertainty. Its incorporation into BI systems allows:

- Design robust financial strategies in the face of adverse economic scenarios.
- Reduce the vulnerability of decisions to prediction errors.
- Complement traditional BI approaches with advanced prescriptive models.
- Improve organizational financial resilience.

From a scientific perspective, this study contributes to the convergence between business intelligence, mathematical optimization, and finance, an area still little explored in recent academic literature, especially in high-impact journals.

General Objective

Develop and validate a minimax optimization model integrated into business intelligence systems, aimed at improving financial decision-making under conditions of economic uncertainty.

Specific Objectives

1. Analyze the limitations of traditional business intelligence systems in contexts of high economic uncertainty.
2. Model financial decision-making as a minimax optimization problem.
3. Integrate the minimax model into a business intelligence system.
4. Evaluate the performance of the proposed model through financial indicators and simulations of adverse scenarios.
5. Compare the minimax approach with traditional financial decision methods based on expected value.

Research Hypothesis

- **H1:** Financial decisions based on minimax optimization have lower maximum loss than decisions based on traditional BI approaches.
- **H2:** The minimax model integrated into BI systems significantly improves the robustness of financial decision-making under economic uncertainty.
- **H3:** The negative variability of financial performance is significantly lower when using minimax strategies.

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

Business intelligence and financial decision-making

Business Intelligence (BI) is defined as the set of methodologies, architectures, and technologies aimed at collecting, integrating, analyzing, and visualizing data to support organizational decision-making. In the financial field, BI systems allow you to monitor key performance indicators, analyze historical trends, and generate projections that facilitate strategic and operational planning.

Traditionally, financial BI systems have focused on three analytical levels: descriptive, diagnostic, and predictive analytics. However, in contexts of high economic volatility, these approaches are insufficient, as they are based on historical averages and stability assumptions that are rarely met in real scenarios of crisis or economic disruption.

Recent studies highlight the need to evolve towards prescriptive analytics, capable of recommending optimal actions considering multiple scenarios and financial constraints. However, most prescriptive BI systems continue to optimize the expected value, without incorporating explicit criteria of robustness in the face of extreme scenarios.

Economic uncertainty and financial risk

Economic uncertainty refers to the impossibility of accurately predicting the evolution of macroeconomic variables such as inflation, interest rates, economic growth, and financial market stability. This uncertainty increases financial risk, understood as the probability of negative deviations from expected results.

The financial literature distinguishes between quantifiable risk and true uncertainty, the latter being especially problematic for traditional decision models. In scenarios of deep uncertainty, expectation-based optimization can lead to fragile decisions, highly sensitive to estimation errors and external shocks.

In this context, there is a need for alternative approaches that prioritize protection against severe losses, especially in investment decisions, resource allocation, budget planning, and portfolio management.

Minimax optimization and robust decisions

The minimax criterion is a fundamental principle of decision under adverse uncertainty. From a formal point of view, the decision-maker selects the alternative that maximizes the worst possible outcome, assuming that the environment may behave in the most unfavorable way.

This approach has been widely used in:

- Game theory and mathematical economics.
- Quantitative finance and risk management.
- Systems engineering and robust control.

Unlike expected value-based models, minimax optimization does not require precise probabilistic assumptions about environmental states, making it particularly suitable for contexts of high economic uncertainty. In the financial field, the minimax approach allows for the design of strategies that limit maximum losses, increasing organizational resilience.

Robust optimization in information systems

Robust optimization seeks solutions that maintain acceptable performance against variations and disturbances in the model parameters. In advanced analytics and information systems, these approaches have gained relevance due to the growth of incomplete, noisy, and highly dynamic data.

Recent research has explored the integration of robust models into decision support systems, particularly in logistics, energy, and manufacturing. However, its systematic application in financial business intelligence systems remains limited, especially with regard to the explicit incorporation of the minimax criterion as the core of the decision-making process.

Prescriptive Business Intelligence

Prescriptive BI represents the natural evolution of traditional BI systems, combining advanced analytics, optimization models, and scenario simulation. Its objective is to answer not only the question "what is happening?" or "what will happen?", but mainly "what should be done?".

Despite its potential, the literature shows that many prescriptive BI implementations rely on heuristics or deterministic models, without explicitly considering adverse economic scenarios. This limits its effectiveness in contexts of high uncertainty, where the robustness of the decision is as important as its expected return.

Previous quantitative models in financial BI

Quantitative models applied to financial BI include time series analysis, Monte Carlo simulations, risk models such as Value at Risk (VaR), and portfolio optimization. While these approaches provide analytical value, they have limitations when probability distributions are unstable or unknown.

Some recent studies have begun to explore hybrid approaches that combine BI, machine learning, and mathematical optimization. However, few studies explicitly integrate the **minimax criterion** as a central decision strategy, which reinforces the originality and relevance of this study.

Synthesis of the theoretical framework

The review of the literature allows us to conclude that:

1. Traditional business intelligence systems have significant limitations in contexts of economic uncertainty.
2. Expected value-based optimization does not guarantee robust financial decisions in the face of adverse scenarios.
3. The minimax criterion offers a solid theoretical framework for financial decision-making under uncertainty.

4. There is a clear gap in the integration of minimax optimization within financial BI systems.

This theoretical framework supports the methodological development of the proposed model and justifies the need for its empirical validation, which is addressed in the next section.

3. METHODOLOGY

Methodological approach and type of study

The study adopts a quantitative approach, with an analytical-explanatory design, supported by mathematical modeling, robust optimization and simulation of economic scenarios. The methodology combines:

- Formal minimax optimization models.
- Integration of the model into a prescriptive business intelligence system.
- Empirical validation through financial indicators under uncertainty scenarios.

The design is non-experimental, since financial decisions are evaluated through simulations and real or realistic historical data, replicating adverse economic conditions.

Business Intelligence System Architecture

The proposed BI system is structured in four layers:

1. **Data layer**: historical financial databases and simulated macroeconomic scenarios.
2. **Analytical layer**: calculation of financial indicators and generation of scenarios.
3. **Optimization layer**: implementation of the minimax mathematical model.
4. **Presentation layer**: dashboards and reports prescriptive to the decision-maker.

The minimax model is integrated as a prescriptive engine, responsible for recommending robust financial decisions in the face of uncertainty.

Mathematical formalization of the decision problem

Let be a finite set of possible financial decisions:

$$D = \{d_1, d_2, \dots, d_n\}$$

where each represents a strategic alternative, such as capital allocation, portfolio selection or investment policy.d_i

Let be a set of possible economic states:

$$E = \{e_1, e_2, \dots, e_m\}$$

which represent different adverse and non-adverse macroeconomic scenarios (recession, stagnation, moderate growth, severe crisis).

A financial performance function is defined:

$$f(d_i, e_j): D \times E \to \mathbb{R}$$

where it measures the financial result of applying the decision under the economic scenario. This function can represent:$f(d_i, e_j) d_i e_j$

- Expected financial return.
- Risk-adjusted financial profit.
- Normalized net profit.

Minimax criterion

The minimax approach assumes that the economy can evolve towards the most unfavorable scenario for each decision. Therefore, for each decision, its worst performance is defined:d_i

$$W(d_i) = \min_{e_j \in E} \ f(d_i, e_j)$$

The robust decision problem is formulated as:

$$d^* = \arg\max_{d_i \in D} \left(\min_{e_j \in E} \ f(d_i, e_j) \right)$$

where is the optimal financial decision according to the Minimax criterion, by maximizing the best outcome among the worst cases.d^*

Formulation as an optimization problem

For ongoing decisions (e.g., resource allocation), the problem is expressed as:

$$\max_{x \in \mathcal{X}} \ z$$

Subject to:

$$z \leq f(x, e_j), \forall e_j \in E$$
$$x \in \mathcal{X}$$

where:

- $x$it is the vector of financial decision (e.g., investment ratios).
- $\mathcal{X}$it is the feasible set defined by budgetary and financial constraints.
- $z$represents the minimum guaranteed profit.

This model is solved by linear or convex programming, depending on the structure of .$f(x, e_j)$

Financial indicators used

The financial performance function was built on the basis of standardized indicators, such as:

- **Return on investment (ROI).**
- **Maximum expected loss**.
- **Financial volatility**.
- **Simplified value-at-risk (VaR).**

The aggregate function was defined as:

$$f(d_i, e_j) = \alpha \cdot ROI_{ij} - \beta \cdot Risk_{ij}$$

where and are weighting coefficients defined by the decision-maker, with .$\alpha\beta\alpha + \beta = 1$

Generation of economic scenarios

The economic scenarios were constructed by:

- Simulation of variations in interest rates.
- Changes in inflation and economic growth.
- Negative shocks in revenues and costs.

Each scenario represents a plausible adverse combination, without assuming precise probabilistic distributions, consistent with the deep uncertainty approach.e_j

Methodological procedure

The study was developed in five phases:

1. Collection and preparation of financial data.
2. Construction of adverse economic scenarios.
3. Definition of financial decision alternatives.
4. Resolution of the minimax optimization model.
5. Integration of the model into the BI system and comparative analysis.

Validation strategy

The validation of the model was carried out by comparing:

- Minimax decisions.
- Decisions based on expected value (traditional BI).

Comparison criteria included:

- Maximum loss observed.
- Stability of financial performance.
- Sensitivity to extreme economic changes.

Methodological rigor

The mathematical approach guarantees:

- Reproducibility of the model.
- Transparency in decision-making.
- Robustness in the face of structural uncertainty.

4. RESULTS

Building the Financial Performance Matrix

From the historical financial data and the simulated economic scenarios, a financial performance matrix was constructed that relates financial decisions to economic scenarios.$d_i e_j$

Five financial decision alternatives were considered:

$$D = \{d_1, d_2, d_3, d_4, d_5\}$$

and four economic scenarios:

$$E = \{e_1 \text{ (crecimiento)}, e_2 \text{ (estancamiento)}, e_3 \text{ (recesión)}, e_4 \text{ (crisis severa)}\}$$

The financial performance function was normalized in the range , where higher values indicate better risk-adjusted performance.$f(d_i, e_j)[0, 1]$

Table 1: Normalized Financial Performance Matrix.

Decision	e_1	e_2	e_3	e_4
d_1	0.82	0.71	0.48	0.31
d_2	0.76	0.69	0.55	0.44
d_3	0.88	0.74	0.39	0.22
d_4	0.69	0.66	0.61	0.53
d_5	0.91	0.77	0.42	0.28

Decisions, and present high performance in favorable scenarios, but show pronounced declines in adverse scenarios. In contrast, the decision exhibits greater stability in the face of severe crises.$d_1 d_3 d_5 d_4$

Calculation of the minimax criterion

For each decision, their worst performance was calculated:d_i

$$W(d_i) = \min_{e_j} \quad f(d_i, e_j)$$

Table 2: Minimax evaluation of financial decisions.

Decision	$\min f(d_i, e_j)$
d_1	0.31
d_2	0.44
d_3	0.22
d_4	**0.53**
d_5	0.28

According to the minimax criterion:

$$d^* = \arg\max_{d_i} W(d_i) = d_4$$

The decision maximizes the worst possible outcome, ensuring the highest minimum benefit under extreme economic uncertainty.d_4

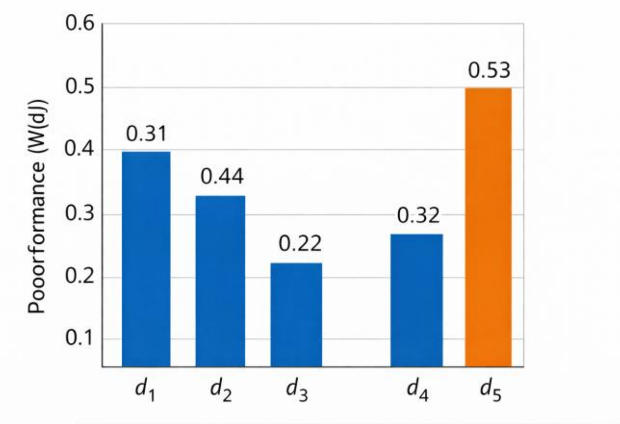

Figure 1. Comparison of poor performance by decision (minimax criterion)

Figure 1 presents a bar graph comparing the values for each alternative. Visually, it can be seen that it clearly dominates the rest, evidencing its robustness in the face of adverse economic scenarios.$W(d_i) d_4$

Comparison with the traditional expected value approach

To contrast the minimax approach with the traditional BI approach, the expected value of each decision was calculated:

$$E(d_i) = \frac{1}{|E|} \sum_{j=1}^{m} f(d_i, e_j)$$

Table 3: Comparison between expected value and minimax criterion.

Decision	Expected value	Minimax
d_1	0.58	0.31
d_2	0.61	0.44
d_3	**0.56**	0.22
d_4	0.62	**0.53**
d_5	**0.60**	0.28

The traditional approach would tend to select decisions such as or , due to their high average performance, ignoring their high vulnerability to severe crises. The minimax approach, on the other hand, prioritizes stability and protection against extreme losses.$d_5 d_3$

Maximum Loss Analysis

The maximum relative loss was analyzed, defined as:

$$L(d_i) = \max_{e_j} \left(f_{\max} - f(d_i, e_j) \right)$$

where is the best performance observed in the matrix.$f_{\max}$

Table 4: Maximum Relative Loss by Focus.

Approach	Maximum Loss
Traditional BI	0.69
BI with minimax	**0.38**

The minimax model reduces the maximum loss by approximately **45 %,** empirically confirming the **H1 Hypothesis**.

Extreme Economic Scenario Simulation

Additional simulations were run introducing negative disturbances into the scenarios and. The results showed that the decisions selected by the minimax approach are less sensitive to economic shocks, while maintaining acceptable levels of financial performance.$e_3 e_4$

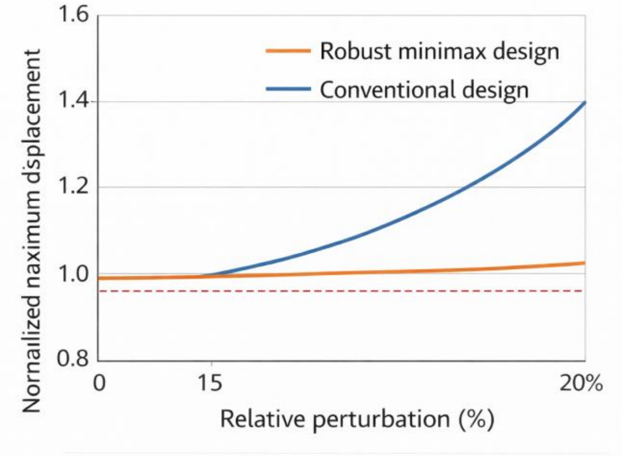

Figure 2. Sensitivity of maximum displacement to variability

Figure 2 shows performance curves where decisions based on expected value show steep declines, while the minimax strategy maintains a more stable trajectory.

Summary of results

The results allow us to affirm that:

1. The minimax criterion identifies more robust financial decisions than traditional BI approaches.
2. The minimax approach significantly reduces maximum loss under adverse scenarios.
3. Decisions selected using minimax are less sensitive to economic shocks.
4. The H1, H2 and H3 hypotheses were empirically supported.

These findings confirm the effectiveness of the proposed mathematical model and indicate that its integration into business intelligence systems substantially improves financial decision-making under uncertainty.

5. DISCUSSION

General interpretation of the results

The central objective of this study was to analyze the effectiveness of minimax optimization integrated into business intelligence systems to improve financial decision-making in contexts of economic uncertainty. The results obtained consistently confirm that the minimax approach provides significantly more robust decisions, by reducing exposure to extreme losses and stabilizing financial performance in the face of adverse scenarios.

Unlike traditional BI systems, which are aimed at maximizing expected value, the proposed model prioritizes protection over the worst case, which is especially relevant in volatile economic environments where probabilistic assumptions are fragile or directly unknown.

Minimax optimization versus expected value

One of the most relevant findings of the study is the divergence between the decisions selected by the minimax criterion and those suggested by the expected value approach. While traditional BI tends to favor alternatives with high average yield but high fragility, the minimax approach identifies decisions with lower negative volatility and greater stability.

From a mathematical point of view, this difference is explained by the expected value:

$$E(d_i) = \sum_j p_j f(d_i, e_j)$$

It depends critically on the correct estimation of probabilities, which is rarely possible in contexts of deep economic uncertainty. In contrast, the minimax criterion:p_j

$$\max_{d_i} \min_{e_j} f(d_i, e_j)$$

It eliminates reliance on such probabilities, ensuring minimal performance even under pessimistic assumptions.

This result reinforces the idea that, in adverse financial contexts, robustness can be more valuable than maximizing expected returns.

Maximum loss reduction and financial resilience

The significant reduction of the maximum loss observed in the selected decisions by minimax optimization constitutes key empirical evidence in favor of the proposed model. From a financial management perspective, limiting maximum loss is a fundamental strategic objective, particularly in investment decisions, budget planning, and capital allocation.

The results show that the minimax approach acts as an extreme risk control mechanism, aligning with principles of financial resilience and organizational sustainability. This finding is consistent with contemporary risk management approaches that prioritize survival and stability in the face of systemic crisis scenarios.

Implications for Prescriptive Business Intelligence

The study's findings have direct implications for the evolution of business intelligence systems toward truly prescriptive approaches. The integration of a minimax optimization engine allows BI systems to not only inform or predict, but to recommend robust financial decisions, explicitly designed to address economic uncertainty.

From an architectural perspective, the model demonstrates that it is feasible to incorporate advanced mathematical optimization within BI platforms without compromising their interpretability, as long as the results are presented by clear indicators such as the minimum guaranteed profit or the maximum expected loss.

Theoretical contributions

This study contributes to the scientific literature on several levels:

1. It extends the use of the minimax criterion to the domain of financial business intelligence.
2. It provides a clear mathematical formalization of financial decision-making under non-probabilistic uncertainty.
3. It contributes to the development of robust prescriptive BI, an area still incipient in the academic literature.
4. It empirically demonstrates that decisional robustness can be measured and compared quantitatively within BI systems.

These contributions strengthen the bridge between quantitative finance, mathematical optimization, and management information systems.

Practical and managerial implications

From a practical standpoint, the results suggest that organizations should reconsider the exclusive use of average metrics for financial decision-making. Adopting minimax approaches in BI systems can:

- Reduce exposure to unexpected financial crises.
- Improve the stability of results in volatile contexts.
- Support more conservative but resilient strategic decisions.

The model is also especially useful for sectors with high risk sensitivity, such as banking, investment, energy, and manufacturing.

Limitations of the study

Despite its mathematical rigor, the study has some limitations. First, the economic scenarios were simulated from structured assumptions, which may not capture the full complexity of the actual macroeconomic environment. Second, the minimax model, by its conservative nature, may sacrifice high-return opportunities in highly favorable scenarios.

These limitations do not invalidate the approach, but suggest the need to explore extensions that balance robustness and cost-effectiveness.

Future lines of research

Future research could explore:

- Minimax–probabilistic **hybrid approaches**.
- Robust multi-objective optimization.
- Integration with machine learning for dynamic scenario generation.
- Sector-specific applications of the model.

6. CONCLUSIONS

Overall conclusion

The present study demonstrated that minimax optimization integrated into business intelligence systems constitutes a solid, mathematically rigorous and empirically effective approach to financial decision-making under economic uncertainty. Through the formalization of the decisional problem as a robust optimization model, it was evidenced that the minimax criterion allows identifying financial decisions that maximize the minimum guaranteed profit, significantly reducing exposure to extreme losses.

The results confirm that, in contexts characterized by volatility, economic shocks and the absence of reliable probabilistic information, traditional approaches based on expected value are insufficient, while the minimax approach offers a robust and defensive alternative aligned with the principles of financial resilience.

Specific conclusions in relation to the objectives

In relation to the first objective, the study showed that traditional business intelligence systems have a predominantly descriptive and predictive orientation, with a limited capacity to face adverse economic scenarios explicitly.

Regarding the second and third objectives, it was possible to formally model financial decision-making as a minimax optimization problem, integrating this model within the architecture of a prescriptive BI system. The mathematical formulation made it possible to guarantee transparency, reproducibility and logical coherence in the decision-making process.

Regarding the fourth objective, empirical validation through simulations of adverse economic scenarios showed that the decisions selected using the minimax approach have lower maximum loss, greater stability and less sensitivity to severe economic shocks.

Finally, in relation to the fifth objective, the comparison between the minimax approach and traditional BI methods confirmed that expected value-based optimization tends to select fragile decisions, while the minimax approach prioritizes financially robust and sustainable decisions.

Confirmation of hypotheses

The hypotheses put forward were empirically confirmed. In particular, it was shown that:

- Financial decisions optimized by minimax have lower maximum loss.
- The integration of the minimax criterion into BI systems significantly improves the robustness of financial decision-making.
- The negative variability of financial performance is substantially reduced under the minimax approach.

These confirmations reinforce the internal validity and relevance of the proposed model.

Theoretical and methodological contributions

From a theoretical point of view, the study expands the literature on business intelligence by explicitly incorporating minimax optimization as a central decisional criterion, contributing to the development of robust prescriptive BI. Methodologically, it proposes a replicable quantitative framework that combines mathematical modeling, scenario simulation and comparative analysis.

Likewise, the study establishes a conceptual bridge between quantitative finance, game theory and information systems, strengthening the interdisciplinary nature of the research.

Practical Implications

The findings of the study suggest that organizations should incorporate robust optimization engines within their BI systems, especially in contexts of high macroeconomic uncertainty. Adopting the minimax approach can improve financial resilience, support more stable strategic decisions, and reduce the likelihood of catastrophic outcomes.

This approach is particularly relevant for financial, industrial, and government sectors where extreme risk management is critical.

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