

Evaluation of innovation in Latin American metal mining: an application of fuzzy logic

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Abstract

Purpose – Board diversity has become a central issue in corporate governance due to its potential role in fostering innovation and long-term strategic thinking. This paper aims to evaluate the influence of board composition – specifically ownership structure, board structure, and demographic diversity – on innovation outcomes in Latin America’s metal mining sector. This study introduces a fuzzy inference system (FIS) to assess the marginal impact of these governance variables on innovation capacity.

Design/methodology/approach – This research applies a Mamdani-type fuzzy logic model to a sample of 12 listed metal mining firms in Latin America. The study draws on corporate governance theory and upper echelons theory to structure three blocks of input variables: ownership (institutional and promoter participation), board structure (size and independence) and demographic diversity (gender and age). Each block is modeled using fuzzy rules and linguistic variables to capture the complexity and interdependence of governance attributes under uncertainty.

Findings – The findings are exploratory and should be interpreted as patterns observed within this specific sample. The results suggest that promoter ownership contributes more significantly to innovation than institutional investors. Smaller boards are associated with higher innovation scores than larger or highly independent boards. Gender diversity demonstrates a meaningful correlation with innovation, while age diversity yields inconclusive results. The fuzzy model enables the ranking of firms based on innovation scores, reflecting governance maturity levels and their alignment with innovation strategies.

Originality/value – This study offers an original contribution by applying fuzzy logic to board-level governance variables, a method not commonly used in the governance-innovation literature. It addresses the analytical gap in evaluating ambiguous and non-linear relationships between governance composition and innovation, particularly in high-capital, low-frequency sectors such as mining. This approach may support firms and policymakers in designing governance frameworks that enhance innovation under conditions of limited data and contextual variability.

Keywords Board composition, Fuzzy inference system, Corporate governance, Innovation, Mining sector, Latin America

Paper type Research article

1. Introduction

Board-level innovation capabilities have gained increasing scholarly attention, particularly in industries characterized by high capital intensity, regulatory exposure, and environmental impact, such as metal mining. In the Latin American context, publicly listed mining companies are relatively few, yet they concentrate significant economic and social importance. The strategic decisions made by their boards—including those related to innovation—have direct implications for productivity, sustainability, and access to international capital markets (Hazaee *et al.*, 2023; Torchia and Solarino, 2025).

JEL Classification — G34, O31 and L72

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Corporate governance frameworks in emerging markets tend to be characterized by high ownership concentration and a frequent overlap between ownership and management (Velte, 2024). This is particularly evident in Latin America's mining sector, where founder-led or state-linked companies still prevail. In such settings, board composition becomes a central mechanism to introduce heterogeneity of thought and oversight capacity. The presence of independent directors, gender diversity, and cognitive variety within the board have all been associated—albeit with mixed results—with firm-level innovation outcomes (Khemakhem *et al.*, 2022; Makkonen, 2022).

The mining sector poses unique challenges for board governance: capital investment cycles are long, technological adoption is costly and path-dependent, and socio-environmental risks require multidimensional stakeholder engagement. These elements reinforce the need to analyze not only whether diversity exists but also how its different dimensions—demographic, structural, and cognitive—contribute to innovative capacity (Khemakhem *et al.*, 2022; Leung and Sane, 2023). Prior research suggests that innovation is less likely to emerge from homogenous groups that reinforce existing worldviews (Hambrick and Mason, 1984), and more likely to emerge when the board integrates differentiated knowledge domains and experiential backgrounds (Miller and Del Carmen Triana, 2009).

Despite the growing body of literature linking corporate governance and innovation, consensus remains elusive. One reason is methodological: traditional linear models may fall short in capturing the complexity and non-linearity of board-level influences on innovation. In response, recent studies advocate for fuzzy logic and other soft-computing techniques to better account for uncertainty, multi-criteria decision-making, and imprecise behavioral patterns in governance systems (Guerrero-Avenidaño *et al.*, 2023; Mancilla-Rendón *et al.*, 2021).

This study builds on those insights by proposing a fuzzy inference system to evaluate the effect of ownership structure, board composition, and diversity dimensions on innovation outcomes in Latin American metal mining firms. By doing so, it aims to fill two gaps: first, the underrepresentation of Latin American governance practices in international innovation literature; and second, the lack of application of non-traditional, holistic methodologies to analyze board dynamics in capital-intensive industries.

2. Literature review

2.1 Role of the board of directors

According to the corporate governance literature, the board of directors in companies can fulfill various roles, such as management oversight (Jensen and Meckling, 1976; Fama and Jensen, 1983), advisor to management (Davis *et al.*, 1997), and resource provider (Pfeffer, 1973; Endrikat *et al.*, 2020, 2021; Hillman and Dalziel, 2003), connecting the company with a wide range of stakeholders to reduce information asymmetries (Velte and Gerwanski, 2020), and even facilitating strategy execution (Charan *et al.*, 2014; Sundaramurthy and Lewis, 2003).

2.2 Boardroom diversity

Ownership structure continues to be a pivotal determinant in how firms allocate resources, particularly in the context of strategic innovation. While traditional views, such as those of Chen *et al.* (2009), emphasize that greater ownership concentration aligns decision-making with long-term goals, recent evidence complicates this notion. For instance, Rao and Bose (2023), and Torchia and Solarino (2025) caution that institutional investors may prioritize short-term returns, potentially undermining exploratory innovation unless embedded within robust governance ecosystems. Empirical findings from Lu *et al.* (2023) further suggest that the effect of institutional ownership on innovation is highly contingent on the quality of board monitoring and alignment mechanisms, reinforcing the importance of configurational perspectives.

Recent studies have placed renewed emphasis on board diversity as a central axis of corporate governance innovation capacity. [Makkonen \(2022\)](#) and [Hazaee et al. \(2023\)](#) both assert that diversity cannot be reduced to a checklist of demographic features. Instead, functional diversity—especially in the form of varied professional experience and international exposure—plays a more determinative role in shaping innovation outcomes. In a meta-review, [Khemakhem et al. \(2022\)](#) identified cognitive diversity as having a statistically significant and positive correlation with innovation performance, whereas demographic diversity (e.g. gender or age) tends to yield weaker and less consistent effects unless embedded in inclusive board cultures.

Gender diversity, however, remains a critical dimension of inquiry. Multiple studies confirm that female directors introduce new perspectives and promote deliberative oversight processes that correlate with a stronger innovation culture ([Makkonen, 2022](#); [Sood et al., 2023](#); [Stevens et al., 2024](#)). Yet, this effect is not always linear. [Ziolo et al. \(2019\)](#) argue that token representation is insufficient and may even backfire in highly homogenous strategic teams. Instead, a critical mass of women on boards is required to generate tangible innovation spillovers, particularly in knowledge-intensive industries.

The structural composition of boards, encompassing size, independence, duality, and promoter involvement, continues to be a subject of debate. Classic arguments ([Hermalin and Weisbach, 2012](#); [Srivastav and Hagedorff, 2016](#)) underscore the agility of smaller boards. This is echoed by [Jiang et al. \(2023\)](#), who found that leaner boards are associated with faster innovation decision cycles. However, others such as [Meng and Shaikh \(2023\)](#) emphasize that structural effects are mediated by contextual factors including country-level governance maturity, firm lifecycle, and industry dynamism. In high-growth environments, duality may constrain dissent and stifle creativity, while in tightly regulated contexts, it may provide leadership continuity essential for long-term R&D strategies ([Olteanu Burcă et al., 2024](#)).

Innovation, in the context of this study, is defined as the organization capacity—articulated through board-level decisions—to deploy new processes, products, and governance mechanisms. This view, rooted in [Belloc's \(2012\)](#) framework, is supported by [Reig-Mullor et al. \(2022\)](#), who argue that board-driven innovation is a governance function, not merely an operational one. Homogeneity in the boardroom may thus inhibit innovation by narrowing the scope of deliberation ([Hambrick and Mason, 1984](#)), while diversity enables organizations to cope with complexity and ambiguity, as shown in [Hoang et al. \(2024\)](#) and [Liern and Pérez-Gladish \(2018\)](#).

Despite this, no universal model of optimal board composition for innovation has emerged. [Qi et al. \(2020\)](#) and [Huang et al. \(2019\)](#) both conclude that innovation outcomes vary widely depending on how governance and innovation are measured. Accordingly, scholars such as [Bottani et al. \(2017\)](#) and [Pislaru et al. \(2019\)](#) advocate for the use of fuzzy logic and fuzzy Analytic Hierarchy Process (AHP) methodologies to evaluate complex multi-dimensional constructs such as board governance. These approaches allow for gradated analysis rather than binary categorization, revealing interaction effects and marginal contributions of each governance element.

In this study, the application of a fuzzy inference system, specifically using Mamdani's model, provides a compelling alternative to traditional linear regression or fuzzy-set Qualitative Comparative Analysis (fsQCA) approaches. The fuzzy system captures the nuanced, overlapping, and often interdependent relationships between ownership structure, board diversity, and innovation performance. As shown in [Suganthi \(2018\)](#) and [Aghajani Bazzazi et al. \(2011\)](#), fuzzy methods offer superior modeling flexibility for complex managerial decisions where precision is limited and subjectivity is inherent. Furthermore, [Crespo and Crespo \(2016\)](#) demonstrate how fuzzy inference systems can accommodate multiple causal configurations, as in their study on national innovation performance using Global Innovation Index indicators.

Therefore, this study responds to recent calls in the literature ([Huang et al., 2019](#); [Kapil and Mishra, 2019](#); [Makkonen, 2022](#)) for greater methodological pluralism in governance research.

By integrating fuzzy logic into board-level analysis of innovation, this research provides a more inclusive framework for understanding how different governance dimensions coalesce to support or hinder innovation, which is particularly relevant for emerging markets, where board composition is evolving and firm-level governance maturity remains heterogeneous.

2.3 Fuzzy logic applications

The growing complexity of corporate governance systems and the multitude of factors influencing board effectiveness have rendered traditional analytical frameworks increasingly inadequate. While conventional approaches have focused on quantifiable metrics such as board independence, gender diversity, or educational background, these simplifications fall short of capturing the deeper dynamics of influence, legitimacy, and complementarity among board members. In this context, fuzzy logic emerges as a powerful methodological alternative—one that is particularly well-suited to modeling non-linear relationships, semantic ambiguities, and linguistic constructs, all of which are inherent to the strategic dimensions of corporate governance.

A wide range of studies have already demonstrated the cross-sectoral versatility of fuzzy-based approaches in decision-making environments characterized by complexity and subjectivity. For example, [Crespo and Crespo \(2016\)](#), drawing on the Global Innovation Index, applied fsQCA to explore the configurations of institutional, human capital, infrastructure, market, and business sophistication conditions that contribute to national innovation performance. Their findings underscored a key principle of fuzzy logic: no single causal condition is sufficient on its own. However, in high-income countries, specific combinations—namely infrastructure and human capital—were found to be sufficient for achieving superior innovation outcomes. This insight parallels the situation in board governance, where the interaction among director attributes, rather than the presence of isolated features, determines governance effectiveness.

Likewise, [Aghajani Bazzazi et al. \(2011\)](#) applied fuzzy methodologies in the mining industry to support equipment selection for open-pit operations. Their approach led to a substantial reduction in computational time while maintaining decision accuracy, outperforming traditional fuzzy AHP models. This case not only exemplifies the operational efficiency of fuzzy logic in multi-criteria environments, but also reinforces its applicability in domains where both technical and qualitative trade-offs must be resolved, a challenge also central to evaluating board composition in corporate governance.

Elsewhere, [Bottani et al. \(2017\)](#) and [Suganthi \(2018\)](#) showed that hybrid techniques such as Fuzzy AHP-VIKOR (Višekriterijumska Optimizacija I Kompromisno Rešenje) not only allow for effective criteria ranking in industrial contexts, but also manage the uncertainty and vagueness of human evaluations—an advantage that can be directly extrapolated to analyzing board member profiles and their strategic relevance. Similarly, [Rao and Bose \(2023\)](#) employed hierarchical fuzzy inference to model qualitative risk factors in complex organizational structures, offering a clear pathway to assess intangible attributes such as sector-specific experience, strategic vision, or network centrality within boardrooms.

Moreover, studies by [Ziolo et al. \(2019\)](#) and [Jiang et al. \(2023\)](#) illustrate how fuzzy logic can be embedded into multicriteria decision-making frameworks such as PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) and DEMATEL (Decision-Making Trial and Evaluation Laboratory) to construct composite environmental, social, and governance (ESG) indicators. Importantly, these works reveal a conceptual shift: governance is no longer viewed as a static structure but as an adaptive system in which financial, ethical, social, and environmental criteria converge—and in which their relative weight varies by context, industry, and country. This insight mirrors the conditions shaping board composition, where the ideal mix of member attributes depends less on normative checklists and more on context-specific combinations of capabilities, values, and contextual legitimacy.

The recent literature has also warned against overly normative and one-dimensional approaches. [Hoang et al. \(2024\)](#), for example, argue that mainstream models fail to capture how subjective stakeholder interactions continuously redefine the meaning of “good governance.” In parallel, [Higashi et al. \(2025\)](#) emphasize that in volatile, uncertain, complex, and ambiguous (VUCA) environments, fuzzy frameworks enable researchers to map institutional maturity trajectories—an analytical lens that is particularly relevant when interpreting boards not as passive oversight bodies but as active strategic agents.

Theoretically, this research aligns with contemporary advances in complex adaptive systems theory and configurational institutional logic. Fuzzy logic thus facilitates a shift from a structural analysis of board composition (who sits on the board and with what credentials) to a functional one (how members interact, how they contribute, and which combinations yield effective governance outcomes).

Despite these advances, the use of fuzzy logic in studies focused specifically on board composition remains limited. This methodological gap contrasts sharply with empirical evidence suggesting that board performance depends not only on individual characteristics, but on complementarities, redundancies, and the strategic alignment of board profiles. There is a compelling opportunity to develop fuzzy models that integrate dimensions such as cognitive diversity, professional trajectory, reputation, genuine (versus formal) independence, and international experience, thus enabling assessments that go beyond compliance and toward understanding the contingent impact of board composition on governance quality.

The literature reviewed highlights an unmistakable trend: as governance environments become more dynamic and multidimensional, so must analytical tools. Fuzzy logic, with its capacity to bridge qualitative and quantitative dimensions under conditions of uncertainty, offers a particularly suitable framework for reassessing how board composition shapes governance effectiveness.

This research seeks to capitalize on that potential. By applying fuzzy logic to the analysis of board composition, it aims to identify critical combinations of director attributes that, in interaction, enhance strategic oversight and governance performance. It thereby contributes to a broader methodological shift, one that moves beyond prescriptive metrics and into the realm of adaptive, context-sensitive governance diagnostics. In doing so, the study not only fills a gap in the literature but also proposes a new lens through which to conceptualize and measure what effective board governance truly means in complex organizational systems.

3. Method

To construct the fuzzy inference system, a Mamdani-type architecture was selected due to its interpretability, transparency, and alignment with rule-based reasoning grounded in linguistic variables. Unlike more mathematically compact models such as Sugeno or Tsukamoto, which are better suited for optimization or adaptive control scenarios, the Mamdani approach enables the encoding of expert knowledge in a form that is intuitively understandable to decision-makers—a critical advantage when dealing with governance systems where transparency, stakeholder communication, and legitimacy of evaluative criteria are paramount.

Corporate governance, by its nature, involves balancing multiple qualitative and semi-quantitative attributes, such as director independence, strategic experience, ethical reputation, and board diversity, many of which are difficult to model using crisp logic or purely statistical methods. The Mamdani fuzzy inference system supports the construction of rule sets in the form *IF x is A AND y is B THEN z is C*, which allows for the incorporation of tacit knowledge from governance experts and practitioners. This is particularly valuable when evaluating board composition, where the optimal mix of characteristics does not emerge from a single dominant variable but rather from nuanced configurations of complementary traits.

Furthermore, the Mamdani model produces outputs in fuzzy sets that can later be defuzzified (e.g. via centroid methods), offering flexibility for both diagnostic evaluation and actionable recommendations. In this research, input variables were selected based on their

theoretical and empirical relevance to board effectiveness, and the rule base was designed following the principles of fuzzy control logic. This methodological choice aligns with prior studies (Suganthi, 2018) that have successfully applied Mamdani models in contexts requiring transparency in complex decision-making, reinforcing its suitability for corporate governance analysis.

Matlab was used to encode the fuzzy inference models, both individually and integrally. The aim is to measure how different combinations of board characteristics (through three blocks or models) of a company determine its ability to achieve a certain level of innovation.

From an initial universe of 49 publicly listed mining companies operating in Latin America in 2021, a filtered sample of 12 companies engaged specifically in metal mining was selected. These firms represent the total population of listed metal mining companies in the region's most relevant capital markets (namely Peru, Chile, and Colombia), where the sector holds strategic economic significance and is subject to public reporting requirements. This deliberate focus on metal mining is justified by its intensive capital requirements, long-term investment horizons, and elevated exposure to international scrutiny regarding ESG practices, all of which make corporate governance particularly relevant.

Data on board characteristics, such as board size, independence, tenure, gender composition, and CEO duality, were extracted from the Bloomberg Terminal, which aggregates publicly disclosed information from company annual reports and securities filings. The decision to use this curated subset of 12 firms responds not only to the feasibility of complete and comparable data collection but also to the specificity of the research objective: evaluating governance structures in capital-intensive sectors where innovation and board oversight are interlinked. This sample size, albeit limited in absolute terms, reflects the full population of listed metal mining firms in the selected countries for the period of analysis, thus preserving internal validity and avoiding selection bias.

Operationally, by employing three fuzzy inference models, each with two input variables, along with specific membership functions and fuzzy rules, a result is obtained for each model. These results, in turn, serve as input for another model (corporate inference), which also features membership functions and rules. Finally, through the defuzzification process, a numerical outcome (INNOV), representing the innovation score, is produced and can be used for ranking or as an input for numerical analysis.

This approach enables us to individually assess the contribution of each variable separately and by block to innovation. Potential combinations of variables that impact the innovation index will ultimately be identified. The process is summarized in Figure 1.

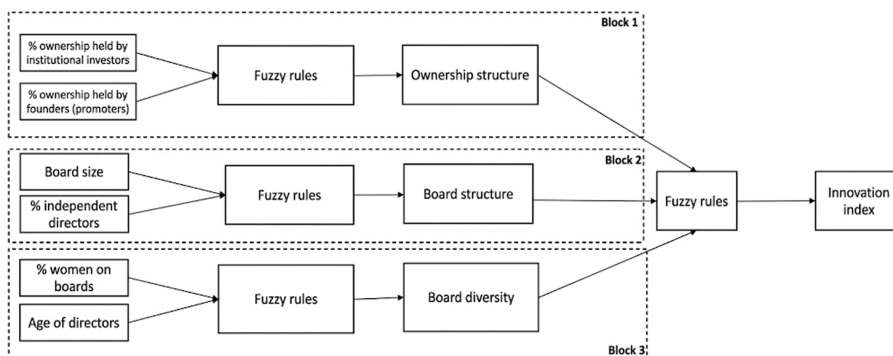


Figure 1. Fuzzy decision model applied to board governance in Latin American metal mining firms. Source: Authors' own elaboration

The rules and membership functions of the blocks were established based on a review of the literature, serving as a proxy for expert judgment, given that a panel of experts could not be assembled for the subject under investigation. More details in [Appendix Table A1](#).

3.1 Membership functions and linguistic variables

In a fuzzy logic system, membership and linguistic variables play an essential role. Membership refers to the extent to which an element or value belongs to a fuzzy set, allowing for degrees of membership within a continuous range. For instance, in a fuzzy set representing the “high” temperature category, a value of 0.8 would indicate a high degree of membership in that category.

Linguistic variables, on the other hand, are used to describe and quantify terms in fuzzy reasoning. These variables represent characteristics or properties of the system under study and are defined by fuzzy sets and membership functions. This approach allows for the modeling and manipulation of imprecise or vague concepts in a more flexible and expressive manner, facilitating communication between experts and non-technical users. For this study, the membership functions and the range of values, by inference block, are summarized in [Table 1](#), and graphically represented in [Appendix Figure A1, A2 and A3](#).

3.1.1 Selection and specification of variables. 3.1.1.1 Block 1: ownership structure. *Percentage of ownership:* The literature recognizes that if a shareholder owns more than 20%, it can be considered a family business ([Villalonga and Amit, 2006](#)). The higher the percentage of family ownership, the more discretionary the application of governance mechanisms might be ([Anderson and Reeb, 2004](#); [Ferramosca and Ghio, 2018](#)). As a proposal, this study assumes that ownership is high with a membership value equal to 1 when the family owns more than 51%, medium from 21% to 50%, and low from 0% to 20% (in many Latin American countries, this is the threshold for being considered a minority shareholder). These thresholds are consistent with prior literature on ownership concentration and family control in emerging markets ([Chen et al., 2009](#); [Anderson and Reeb, 2004](#)).

Institutional investors (II): Institutional investors are critical for shareholders as they not only provide financial capital but also bring knowledge, best practices, and competitive pressures to the industries in which they invest. Additionally, some authors suggest that institutional investors may have close relationships with management ([Ferreira and Matos, 2008](#); [Gillan and Starks, 2003](#)). When there is a greater presence of institutional investors, executives tend to align more closely with the company’s interests ([Colpan and Yoshikawa, 2012](#)).

3.1.1.2 Block 2: board structure. *Board size:* Agency problems can be more severe with larger boards ([Cheng, 2008](#)), as the CEO can influence and/or control the board, making quick

Table 1. Variable descriptions

Evaluation parameter	Linguistic variable name	Linguistic value	Universe of discourse	Membership function
Ownership structure effect on innovation	OwnStr	Low	[0.100]	[−45, −5, 15, 30]
		Medium	[0.100]	[20, 35, 55]
		High	[0.100]	[45, 80, 100, 120]
Board structure effect on innovation	DirStr	Low	[0.100]	[−45, −5, 15, 30]
		Medium	[0.100]	[20, 35, 55]
		High	[0.100]	[45, 80, 100, 120]
Diversity structure effect on innovation	DivStr	Low	[0.100]	[−45, −5, 15, 30]
		Medium	[0.100]	[20, 35, 55]
		High	[0.100]	[45, 80, 100, 120]
Source(s): Authors’ own elaboration				

decision-making difficult. Larger boards are often associated with lower R&D investment due to an aversion to risky projects. A board with fewer than three members is undesirable in public companies, and the ideal board size has been established at 12 members.

Board independence: When the board is mostly composed of independent directors, it can prevent opportunistic behavior by controlling shareholders or management, thereby protecting the rights of all shareholders (Anderson and Reeb, 2004; Matzler *et al.*, 2015). A high value, ranging from 0.5 to 1, indicates a greater likelihood that the CEO is not part of the controlling group and that there is increased openness to innovation. A medium value ranges from 0.2 to 0.49, while a low value, ranging from 0 to 0.19, indicates that the controlling group has stronger control over corporate governance mechanisms as well as investment and innovation decisions.

3.1.1.3 Block 3: demographic diversity. The third block, analyzed independently, measures the contribution of female participation on the board and the median age of directors to assess a company's innovation potential based on these board variables.

Female participation: Women have the capacity to bring innovative ideas and networks, reducing transaction costs associated with obtaining information and facilitating the proposal of new ideas or the questioning of doubtful ones. This helps firms seize opportunities, increase sales, improve margins, and enhance their financial performance (Solakoglu and Demir, 2016).

Age of directors: More experienced directors (longer tenure as directors) generally respond better to changes in the business environment (Finkelstein and Hambrick, 1990). Some authors argue that younger groups of directors (Bezrukova *et al.*, 2009) tend to bring fresh ideas and a greater capacity for innovation.

3.2 Robustness and sensitivity analysis

Given the reduced sample size of 12 firms, which nevertheless represents the full population of listed metal mining companies within the scope of the study, robustness is addressed from a structural rather than an inferential perspective. The objective is not to assess statistical significance but to evaluate the stability of the fuzzy inference system under plausible variations in its internal specification. This approach is consistent with the exploratory nature of the analysis and with the logic of fuzzy modeling, where uncertainty is embedded in model structure rather than in stochastic error terms.

Robustness is examined by means of a sensitivity analysis that focuses on the core components of the fuzzy system. First, the parameters of the membership functions associated with the input variables are systematically perturbed within bounded ranges ($\pm 10\%$), while preserving their ordering and minimum width to avoid degenerate fuzzy sets. These perturbations reflect reasonable uncertainty in the specification of linguistic thresholds derived from expert judgment. Second, the analysis implicitly captures variations in the relative contribution of each governance block to the final innovation index, as changes in membership functions propagate through the hierarchical structure of the model, affecting the inferred weights assigned to ownership structure, board structure, and board diversity.

The sensitivity analysis is conducted using a Monte Carlo simulation, generating a large number of alternative model realizations. For each scenario, the innovation index is recomputed and compared with the baseline results. The outcomes are summarized using distributional statistics that capture shifts in the mean and median innovation scores, as well as changes in relative rankings across firms.

A tornado diagram (Figure 2) illustrates the relative influence of each input variable on the final innovation index under structural perturbations, highlighting the variables with the greatest impact on model outputs. The tornado diagram summarizes the structural sensitivity analysis by ranking governance variables according to their impact on the innovation index under $\pm 10\%$ uncertainty in membership function parameters. The horizontal bars represent the

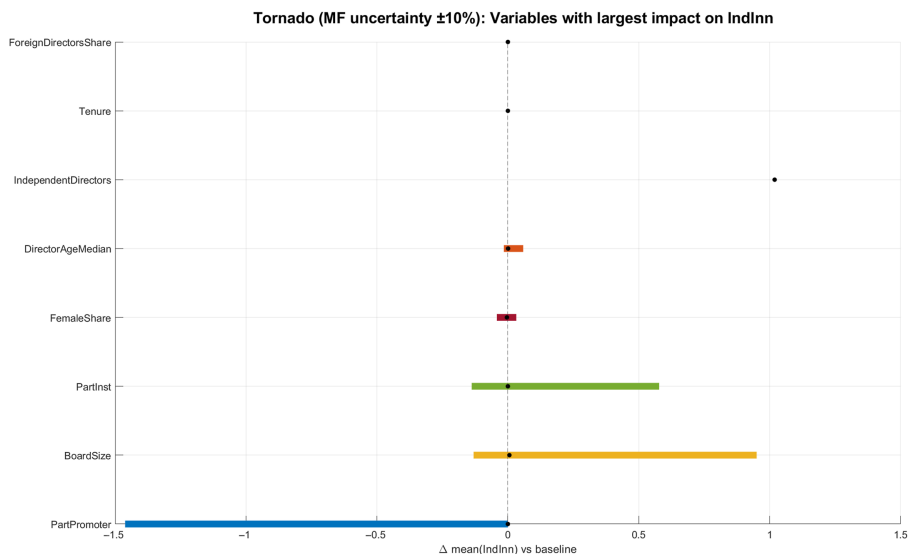


Figure 2. Tornado diagram applied to the innovation index

range between the 5th and 95th percentiles of changes in the mean innovation score relative to the baseline.

Two variables clearly dominate the sensitivity profile of the model. Promoter ownership exhibits the widest dispersion, indicating that small perturbations in its fuzzy specification generate the largest variation in the innovation index, with a strongly asymmetric effect concentrated on the negative side. Board size follows as the second most influential variable, showing a substantial but comparatively narrower range of impact, mainly in the positive direction. Institutional ownership lies in an intermediate position, with a moderate yet noticeable effect on the results. The remaining governance variables display only marginal sensitivity and do not materially affect the innovation index under the $\pm 10\%$ uncertainty scenario.

In contrast, variables related to board diversity and composition (including female share, median age of directors, tenure, foreign directors, and independent directors) display narrow ranges centered close to zero. This suggests that reasonable perturbations in their membership functions do not materially alter the overall innovation ranking.

Overall, the tornado plot indicates that the model's behavior is driven by a limited set of governance variables, while the remaining inputs contribute to the stability of the fuzzy inference system.

4. Results

The individual evaluation of each component of the proposed fuzzy inference model allows us to determine the marginal importance of each variable within the system. Regarding Block 1 (evaluation of innovation from the board ownership perspective), it is observed that higher proportions of institutional investor participation have little to no effect on increased levels of innovation. In contrast, higher levels of promoter involvement result in higher innovation scores. Among the 12 companies presented, Company 7 has the highest score.

The surface illustrates how different combinations of institutional and promoter ownership are translated into an ownership-structure innovation score. Darker regions indicate higher

inferred innovation scores. Figure 3 shows nonlinear interactions where higher promoter control and balanced institutional participation lead to higher inferred innovation levels.

Regarding Block 2 (measurement of innovation from the board structure), represented in Figure 4, the presence of independent directors does not appear to have a significant impact on innovation. However, board size does, with smaller boards having a greater impact on innovation. Among the 12 companies presented, Company 12 has the highest score.

The surface plot shows how the inferred board-structure innovation score varies with board size and the share of independent directors. Higher innovation scores emerge for relatively small to medium boards combined with a moderate to high presence of independent directors. In contrast, larger boards or low levels of independence are associated with lower scores, reflecting diminishing effectiveness of board monitoring as size increases.

On the other hand, regarding Block 3 (innovation from the board's demographic diversity perspective), see Figure 5, any level of female participation is expected to lead to increased innovation, according to the literature. The age of directors does not generally have a significant influence on innovation. Based on this evaluation, no company dominates in terms of innovation from the board.

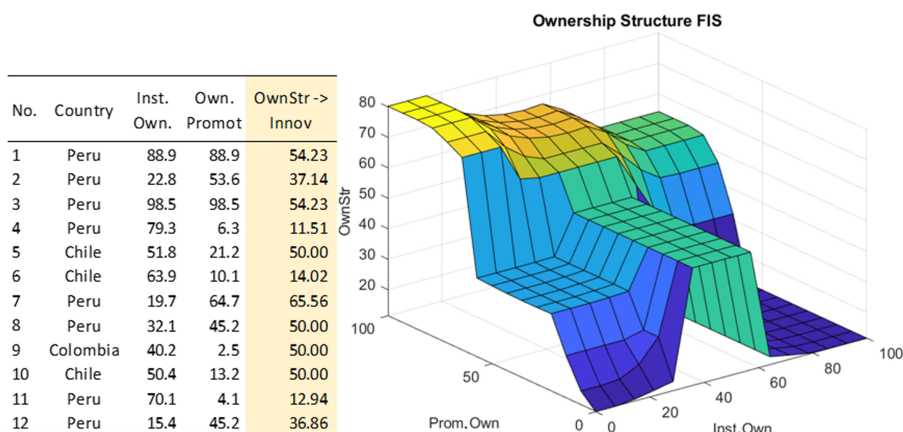


Figure 3. Evaluation of the ownership structure – innovation inference block

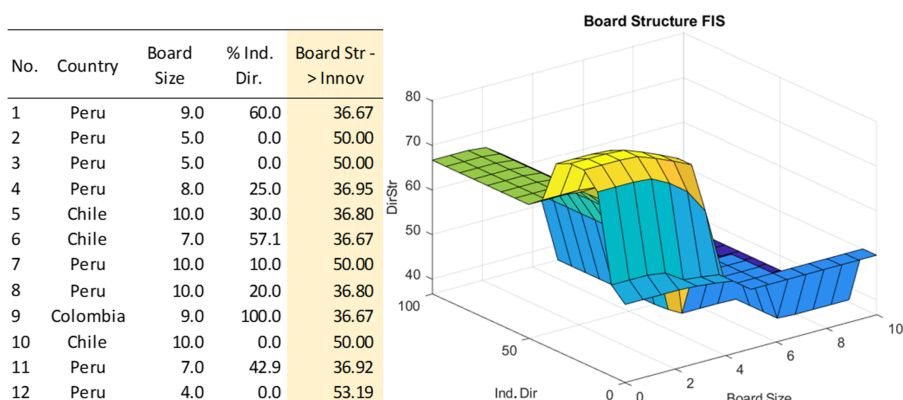


Figure 4. Evaluation of the board structure – innovation inference block

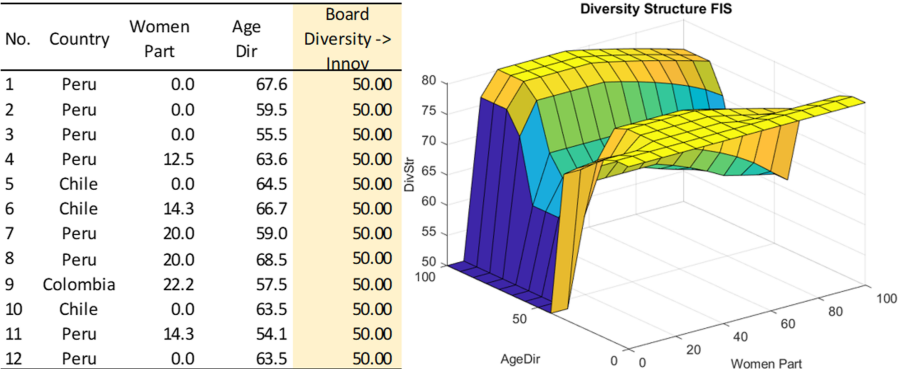


Figure 5. Evaluation of the board diversity – innovation inference block

The surface plot illustrates the nonlinear interaction between the median age of directors and female board participation in shaping the diversity-related innovation score. Higher values are associated with balanced age profiles and moderate to high female representation, while very low age diversity or minimal female participation leads to substantially lower scores.

These analyses provide valuable insights into the innovation landscape shaped by boards. Figure 6 shows higher innovation in firms with moderate ownership, smaller boards, and more independence, while larger boards or concentrated ownership reduce effectiveness; no firm consistently dominates across dimensions.

To assess the stability of the rankings, a sensitivity analysis was conducted. The main results remain qualitatively stable under reasonable perturbations of membership functions and block weights.

5. Discussion of results

5.1 Implications for theory

The disaggregated evaluation of each component of the fuzzy inference system offers a nuanced perspective on the marginal influence of distinct governance variables on firm-level innovation. When examining Block 1, which captures ownership structure as a determinant of innovation, the findings are particularly revealing. The data show that institutional investor ownership, despite being frequently associated with monitoring intensity and resource access, exerts little to no positive effect on innovation outcomes. This result aligns with findings by

No.	Country	Inst. Own.	Prom. Own	Board Size	% Ind. Dir.	Wom. Part.	Age Director	OwnStr -> Innov	Board Str -> Innov	Board Diversity -> Innov	Innovation Index (II)	RK II
1	Peru	88.9	88.9	9.0	60.0	0.0	67.6	54.23	36.67	50.00	73.61	3.0
2	Peru	22.8	53.6	5.0	0.0	0.0	59.5	37.14	50.00	50.00	56.06	5.0
3	Peru	98.5	98.5	5.0	0.0	0.0	55.5	54.23	50.00	50.00	73.61	3.0
4	Peru	79.3	6.3	8.0	25.0	12.5	63.6	11.51	36.95	50.00	76.32	2.0
5	Chile	51.8	21.2	10.0	30.0	0.0	64.5	50.00	36.80	50.00	56.06	5.0
6	Chile	63.9	10.1	7.0	57.1	14.3	66.7	14.02	36.67	50.00	76.32	2.0
7	Peru	19.7	64.7	10.0	10.0	20.0	59.0	65.56	50.00	50.00	79.35	1.0
8	Peru	32.1	45.2	10.0	20.0	20.0	68.5	50.00	36.80	50.00	56.06	5.0
9	Colombia	40.2	2.5	9.0	100.0	22.2	57.5	50.00	36.67	50.00	56.06	5.0
10	Chile	50.4	13.2	10.0	0.0	0.0	63.5	50.00	50.00	50.00	56.06	5.0
11	Peru	70.1	4.1	7.0	42.9	14.3	54.1	12.94	36.92	50.00	76.32	2.0
12	Peru	15.4	45.2	4.0	0.0	0.0	63.5	36.86	53.19	50.00	68.81	4.0

Figure 6. Dimensions and innovation rankings. Note: The red arrows highlight firms whose innovation rankings change most significantly across governance blocks

Lu *et al.* (2023), who noted that the influence of institutional ownership on innovation tends to be conditional and often diluted by short-term return expectations.

Conversely, promoter ownership, interpreted as an indicator of strategic alignment and long-term vision, demonstrates a robust positive relationship with innovation scores. This is consistent with Meng and Shaikh (2023), who found that controlling shareholders often possess tacit knowledge and exert stronger strategic direction over R&D and innovation-related investments. Within this block, Company 7 emerges as the top performer, reinforcing the hypothesis that ownership concentration in promoters may serve as a catalyst for innovation in certain governance configurations.

Turning to Block 2, which evaluates the board's structural characteristics, the findings challenge some prevailing assumptions in the governance literature. Specifically, the presence of independent directors appears to have a limited impact on innovation performance. This observation is echoed by Hoang *et al.* (2024), who argue that the formal independence of directors is not necessarily a proxy for strategic effectiveness, especially in environments where information asymmetry and board passivity persist.

Instead, board size plays a more prominent role, with smaller boards associated with higher innovation outputs. This corroborates the argument of Jiang *et al.* (2023), who highlight that compact boards facilitate faster decision-making, greater cohesion, and more agile strategic responses, traits that are critical for fostering innovation. Company 12, with its lean board structure, exemplifies the potential advantages of board downsizing in innovation-oriented governance design.

Block 3, which focuses on demographic diversity within the board, presents a more nuanced landscape. The data suggest that female participation, even at minimal levels, tends to correlate positively with innovation. This result is strongly aligned with the findings of Sood *et al.* (2023) and Ziolo *et al.* (2019), who emphasized that gender diversity introduces cognitive variety and improves risk assessment, ultimately supporting innovation in boardroom dynamics. In contrast, directors' age does not exhibit a clear or consistent influence, reinforcing the claim by Pislaru *et al.* (2019) that generational factors may be overshadowed by other demographic or experiential traits in innovation-driven decisions. Interestingly, this block does not yield a dominant firm in terms of innovation performance, indicating that demographic composition alone is not sufficient to explain firm-level variance in innovation, but may instead operate as an enabler within broader configurations.

Collectively, these results reinforce the importance of a configurational and fuzzy-logic-based approach to corporate governance. They reveal that no single variable exerts a universally dominant influence across all firms; rather, the interplay between ownership, structural, and demographic attributes must be considered holistically. These patterns substantiate the proposition advanced by Crespo and Crespo (2016) that high-performance outcomes such as innovation arise not from isolated conditions but from context-dependent combinations of factors. Moreover, the use of a Mamdani fuzzy inference system proves particularly appropriate for capturing these subtle interactions, allowing for the incorporation of expert knowledge and nuanced governance judgments, as illustrated in cases such as Suganthi (2018) and Higashi *et al.* (2025).

The study findings suggest that promoter-driven ownership, compact board size, and gender-diverse composition are relatively stronger levers for board-induced innovation than institutional ownership, formal independence, or the age of directors. These insights provide a compelling foundation for refining governance models that prioritize strategic alignment over formal compliance, and complementarity over homogeneity in board composition.

5.2 Practical implications

For firms aiming to enhance their innovative capacity through governance reform, these findings offer concrete insights. First, strategies to increase promoter engagement—particularly when founders or long-term shareholders possess tacit knowledge—can

strengthen the innovation trajectory. Second, optimizing board size, rather than simply expanding board independence, may yield better innovation outcomes, especially in dynamic sectors requiring rapid decision-making. Third, enhancing gender diversity on boards, even incrementally, can contribute positively to innovation ecosystems, although diversity policies should be coupled with broader inclusion strategies to ensure substantive contributions.

Corporate leaders and policymakers may find this fuzzy-logic-based approach especially useful in designing governance diagnostics or scenario analyses, as it enables flexible modeling of interactions between governance attributes. This is particularly important in emerging markets, where governance practices often evolve in hybrid or transitional institutional environments.

5.3 Limitations and future research

Despite its methodological contributions, this study is not without limitations. The sample size—limited to 12 companies—raise concerns about external validity and the generalizability of the findings. While the fuzzy model provides valuable insights into relative importance and configurational logic, the small and potentially non-representative sample constrains the strength of causal inferences. Additionally, the cross-sectional nature of the analysis limits the ability to observe temporal dynamics or innovation lag effects, which may be critical in certain industries.

Future research should aim to expand the sample size across sectors and countries, incorporate longitudinal data, and explore potential interaction effects among governance variables using advanced fuzzy clustering or hybrid models (e.g. fuzzy-DEMATEL, fuzzy-QCA). The inclusion of additional variables, such as board tenure, stakeholder engagement practices, or ESG orientation, may further enrich the explanatory power of the model. Finally, while these findings are exploratory, they open new avenues for theorizing and measuring the complex interplay between governance structures and innovation strategies. The fuzzy logic framework provides a useful starting point for building a more granular, context-sensitive understanding of how boards contribute to value creation beyond traditional financial indicators.

6. Conclusion

This study sought to evaluate the relationship between board characteristics and firm-level innovation using a Mamdani-type fuzzy inference system. By operationalizing governance dimensions into three analytical blocks (ownership structure, board structure, and demographic diversity), the model allowed for the estimation of marginal and combined effects of board-level variables on innovation outcomes. In the context of this study, fuzzy logic proved useful for managing the ambiguity and interdependence inherent in governance configurations. As such, it offers a promising framework for modeling complex relationships that traditional linear models may fail to capture.

The results reveal that not all commonly accepted governance features uniformly foster innovation. Within the ownership dimension (Block 1), the model identified a negligible or null influence of institutional investor participation on innovation, suggesting that the presence of institutional capital, in isolation, may be insufficient to stimulate long-term innovative activity. In contrast, higher levels of promoter involvement—often associated with strategic continuity and founder influence—were found to be positively correlated with innovation scores. Company 7, characterized by strong promoter ownership, led performance in this domain.

In the board structure dimension (Block 2), the presence of independent directors did not emerge as a significant driver of innovation. Instead, board size proved to be a more salient variable, with smaller boards consistently linked to higher innovation scores. This finding suggests that leaner governance bodies may be more conducive to agile decision-making and

strategic focus. Company 12, featuring a compact board configuration, recorded the highest performance in this block.

With respect to demographic diversity (Block 3), female representation on boards showed a positive but modest association with innovation. This is consistent with literature highlighting the value of gender diversity in enhancing cognitive pluralism and organizational creativity. Conversely, the age of directors was not found to exert a meaningful influence on innovation outcomes. Moreover, no single firm demonstrated clearly dominant innovation performance in this dimension, hinting at either the presence of threshold effects or the need for additional conditioning variables to fully capture the influence of demographic attributes.

Supplementary material

The supplementary material for this article can be found online.

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