A reliability model for assessing corporate governance using machine learning techniques

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CITATION: Hernandez-Perdomo, E., Guney, Y., and Rocco, C. A reliability model for assessing corporate governance using machine learning techniques. *Reliability Engineering and System Safety*, 2019, Volume 185, pp 220-231.

https://doi.org/10.1016/j.ress.2018.12.027

Abstract

Corporate governance assesses the efficiency and effectiveness of companies' operations and decisions to ensure value creation for shareholders and optimal risk taking. As investors' decision making process largely depends on financial information and corporate reports, transparency is capital for the stability of a company, or even the stability of a country via the corporate sector. This research introduces the system reliability theory to properly model the behavior of companies regarding their corporate governance mechanisms. We propose the assessment of the corporate governance framework by mapping its inputs as components (either in operating or failed state) along with firm characteristics to determine an approximate Structure Function that enables alternatively modeling the functioning of the system, quantifying its reliability and detecting critical components. The advantage of the proposed mapping approach is illustrated using a sample of 1,109 U.S. listed companies during the period 2002-2014, reporting financial and non-financial information as components of the corporate governance system and the return on assets as the system output. The proposed approach is also useful for modeling other non-engineering sub-systems; companies, financial markets or even economies would be exposed to significant risk if these systems do not function properly.

Keywords

Corporate Governance, Financial Risk, Firm Performance, Machine Learning, System Reliability, Structure Function

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1. Introduction

Corporate governance focuses largely on internal mechanisms related to board function and structure, stock ownership structure, and remuneration incentives as well as external mechanisms that consider investor protection, law enforcement, and property rights. In general, scholars emphasise that corporate governance could be considered as a system for assessing corporate control and risks from conflicts of interests and misalignment between managers and shareholders (investment risk), or between large shareholders and minority shareholders (equity risk); see, for example [1-4].

Corporate governance systems have also been in the centre of the major world scandals and systemic risks, which involve unethical behaviour [5], shareholder value destruction [6], and accounting fraud [7], to name some. For instance, during the 2007-2008 financial crisis many problems arose, which were notably associated with top managerial remuneration, lack of transparency, risk management, and lack of regulation [6, 8-10]. Despite the difficulties, market participants continue to require more information related to corporate governance, and decision makers are more aware of companies' transparency [6].

In terms of the corporate governance framework, several authors ([11-13], among others) have perceived it as a system composed of "practices" and "mechanisms" that ensures that managers' practices are aligned to shareholders' interests through the board of directors in order to create a stable environment to generate profits and reduce business risks [3-4].

As an example, many studies suggest that corporate governance ratings and indices (e.g., information disclosure, reporting and compliance) could be linked to firm performance, namely the well-known return on assets (ROA) [7, 14]. In this case, corporate governance performance and its particular aspects such as board size and independence, and corporate ownership structure are considered as the input variables of the system while ROA is defined as the system output. We argue that the lack of proper "functioning" in the input variables could affect system output. For example, the benefits of a company or its financial stability could be affected. At the macro level, those effects could put under risk the money and capital markets and the economy of a country.

Cormier et al. [15] and Mahr et al. [16] emphasise that information disclosure is a key aspect for assessing whether boards are effective in controlling managers and aligning them to the shareholders' interests, and consequently to their corporate governance practices. In other words, transparency is a key aspect to make companies and financial markets more reliable, mainly because it reduces monitoring costs incurred by investors' demand when they want to gather appropriate financial and non-financial information.

In this paper, departing from the extant literature, we propose a study of the corporate governance framework from the system reliability theory point of view, mapping input variables to system components and analysing under what conditions the corporate governance system "operates or fails". To this end, we derive its approximate structure function (*SF*) [17] that mimics the functioning of the system for given states of its components. Using the *SF*, decision makers could analyse, for example: 1) which components affect the system the most; 2) what type of corporate governance components enhance the functioning of companies; and 3) the probability that the system is operating. To the best of our knowledge, this type of assessment, for the corporate governance framework, has not been considered in the literature.

The proposed mapping approach is implemented on a case study containing 1,109 listed companies in the U.S. market during the time period 2002-2014 (8,412 company-year observations). These companies have reported financial information available in Reuters Datastream™ and Thomson One™ information systems, and non-financial information (i.e., corporate governance) in the segment ASSET4 ESG in Datastream for the mentioned period.

As in many other publications not directly related to the engineering area, such as health care [92-94], financial crisis [8], political decisions [95], evaluation of priorities in the business process [96], risk perception [97-98], organizational learning [99-100], security of energy supply of a country [101], food safety management [102], risk governance [103], risk and performance management [104-105], quality and safety models [92], organizational failures [96], among others, the proposed approach considers a specific system and discusses aspects of financial implications, managerial perspectives or risk interpretation.

The rest of the paper is organised as follows. Section 2 introduces corporate governance as a system, and describes the role of companies' disclosure and transparency on the system stability. Section 3 presents a general overview about the reliability of a system, and how the structure function can be derived. Section 4 describes the main aspects to map corporate governance components and specific conditions in this field. Section 5 presents the characteristics of the case study while Section 6 shows the main results and discussions. Finally, section 7 concludes the papers and outlines some future research directions.

The acronyms (the singular and plural of an acronym are always spelled the same) and notations used in this paper are shown as below:

Acronym	Meaning
ARE	Approximated Reliability Expression
CGA	Corporate Governance Assessment
DT	Decision Tree
LLM	Logic Learning Machine
ML	Machine Learning
NN	Neural Networks
RE	Reliability Expression
ROA	Return on Assets
SDP	Sum of Disjoint Products
SVM	Support Vector Machine

Notation	Explanation
x	$(x_1, x_2, \ldots, x_N)^T$ state vector, denotes the state of all the components of a system
E[]	Expected value operator
N	Number of components
P, Q	$(P_1, P_2, \ldots, P_N)^T$, $(Q_1, Q_2, \ldots, Q_N)^T$ state vector of probabilities
P_i	Probability that component i is operating.
Q_i (=1-P_i)	Probability that component i is failed.
R	Reliability of the system
$SF(\boldsymbol{x})$	The structure function
x_i	The state of a component, binary
y	Output of the system

2. Corporate governance system and disclosure

Corporate governance is a set of practices and mechanisms (hereafter components) that assures that companies can allocate their resources according to their objectives but also they are managed in the best interest of shareholders [6, 18-20].

Lipton & Rosenblum [13] were one of the first authors who introduced corporate governance as a system. They claim that this system works in two perspectives: i) it ensures alignment between managers and shareholders, and ii) it creates a stable environment to generate sustainable profits. Alterations on the system components could harm companies' benefits and even an economy overall.

Corporate governance can be divided into internal and external sub-systems. The internal sub-system is related to firm level mechanisms to deal with conflict of interests among shareholders and those who control business [5, 21-22]. The external sub-system considers country level aspects (e.g., investor protection, law enforcement, property rights, and government intervention) to protect stakeholders from corporate fraud or theft [3-4].

Table 1 reports some scholarly perspectives about this system, which provides the guidelines to evaluate it according to the lenses of reliability systems.

Table 1
Corporate governance as a system approach

According to these authors, corporate governance can be seen as a system with many input variables or components (practices, mechanisms, accountabilities, and so forth) where managers, shareholders, and the board of directors are aligned to make companies to perform their required system output function such as profit generation, value creation, among other aspects. Furthermore, decision makers evaluate the level and types of information disclosure about corporate governance practices, and assess whether it is functioning properly [27-29].

Table 2 presents some literature related to financial disclosure and reporting, the level of firm transparency, which justifies the means to analyse and evaluate corporate governance as a system.

Table 2
Transparency (reporting and disclosure) into a corporate governance system

The literature reported in Table 1 and Table 2 only analyses the determinants (i.e., explanatory power – traditional regression analysis) of corporate governance components on firm performance. However, because the majority of components (categorical or nominal variables such as comply or not, disclose or not, report or not, and so forth) present high degrees of time invariant, low variability across time, consistently estimating the effects of time invariant variable in a regression model is problematic [107]. However, far too little attention has been paid to the usage of a reliability model, where decision makers can assess which corporate governance inputs (operating or failure) are important for the correct functioning of the system.

Finally, it can be noted that disclosure or lack of reporting allows characterising whether companies have their corporate governance components in an operating or failed state. This suggests that corporate governance can be modelled as a *reliability* system.

From this review, several aspects can be summarised:

- There is a set of N input variables $\boldsymbol{x} = (x_1, x_2, \ldots, x_N)$ (binary or continuous). Each company could be evaluated using this set of variables.
- There is a set of output variables (binary or continuous) that assesses the performance of the company.
- The set of input variables, even if defined from theoretical or practical aspects, is not complete.
- The possible relationship between $\boldsymbol{x}$ and one selected output y is given by $y = F(\boldsymbol{x})$, where F is an unknown function that must be determined or at least approximated.

These considerations allow us to map the corporate governance assessment (CGA) to a well-known mathematical model used in the reliability field through a *SF*, which is capable of modelling the functioning of the system for given states of its corporate governance components.

3. Structure Function of a System

In this section, we briefly review the concept of the structure function of a system, its definition, the relationship with the reliability of a system and how it is derived in simple cases [85-91]. In addition, we describe how the structure function could be found in systems where the relationship between the components and the output of a system is unknown, using computational techniques derived from the machine learning paradigm [39].

3.1. Introduction

The structure function is a classical and powerful tool for any reliability quantification, such as the estimation of the probability of failure of a system, comparison among system designs or the identification of those components "that are most critical, from a reliability/safety point of view and that should be given priority with respect to improvement" [85] Even if new aspects related to *SF* have been presented in the literature (e.g., imprecise probability, signature function or the survival signature (see [85] and references therein)) we consider that the mapping approach based on classical *SF* is enough for our main purpose.

We consider a system defined by: a) components or elements in two possible states (operating and failed); b) states are statistically independent events; and c) the system is coherent [17, 91].

The state x_i of the i^{th} component is defined as [17, 35]:

$$x_i = \begin{cases} 1 \ (operating\ state) \\ 0 \ (failed\ state) \end{cases} \tag{1}$$

Let P_i and $Q_i = 1\text{-}P_i$ be the probabilities that component i is operating or failed respectively. Note that $\mathrm{E}[x_i] = P_i$.

Let $\boldsymbol{x} = (x_1, x_2, \ldots, x_N)^{\mathrm{T}}$ be a vector representing the state of a system containing N components.

Then, the performance of the system could be described as [17, 85-86, 91]:

$$y = SF(\boldsymbol{x}) = \begin{cases} 1, \text{if the system is operating in this state} \\ 0, \text{if the system is failed in this state} \end{cases} \tag{2}$$

where *SF* is the Structure Function which expresses the state of the system in terms of the states of its components [91].

The $SF{:}\{0,1\}^N \rightarrow \{0,1\}$ is a Boolean function, composed by terms associated to the state of the components x_i (and/or complements $\overline{x_i}$) that perfectly describes the operation of a system. To illustrate, consider a system modelled by the network in Figure 1 [36]. In this network, components 1 and 3 are functionally connected in series, components 2 and 4 are functionally connected in series, and their equivalents 1-3 and 2-4 are functionally connected in parallel. The *SF* of this network could be directly derived, taking into account that the system is in the operating state if (components 1 AND 3) are operating OR (components 2 AND 4) are operating, that is: $SF(\boldsymbol{x}) = x_1x_3 + x_2x_4$. In this expression, the term x_1x_3 is read as x_1 AND x_3 while the "+" is read as OR.

Figure 1. A four-component network [36]

The *SF* "plays an essential role in reliability assessment" [85]. In fact, the reliability of the system could be calculated as [86-91]:

$$R = P(SF(\boldsymbol{x}) = 1) = \mathrm{E}[SF(\boldsymbol{x})] \tag{3}$$

In general, the *SF* could be transformed to an equivalent expression where only sum of disjoint products (SDP) are used [47, 59]. From this transformed expression it is easy to derive the symbolic Reliability Expression (RE) of the system: 1) logical sums and products are replaced with sums and products of real numbers; and 2) every term x_i or complement $\bar{x}_i$ is replaced by P_i or Q_i respectively [36,59]. For the system in Figure 1, the original $SF(\boldsymbol{x}) = x_1x_3+x_2x_4$ is converted into the equivalent expression $SF(\boldsymbol{x}) = x_1x_3 + \bar{x}_1x_2x_4 + x_1x_2\bar{x}_3x_4$ where only SDP terms appear. Finally, $RE(\boldsymbol{P},\boldsymbol{Q}) = P_1P_3 + Q_1P_2P_4 + P_1P_2Q_3P_4$, where $\boldsymbol{P}$ and $\boldsymbol{Q} = \mathbf{1}\text{-}\boldsymbol{P}$ are the vectors representing the probability of operation and failure of the components respectively.

The numerical evaluation of the RE could be used, for example to: *i*) determine the reliability of the system; *ii*) solve optimisation problems (e.g., the classical reliability allocation problem [37]); or *iii*) determining the importance of the components (e.g., by using the Birnbaum index or any other importance measures [38]).

However, in many real cases, the *SF* of a system could not be directly derived (e.g., the relationship among the state of components and the state of the system is unknown). In these cases, computational approaches are suggested to determine the *SF*. In the next section, we describe one of these approaches, based on the machine learning paradigm [39].

3.2. Machine learning approach for determining SF

3.2.1 Introduction

When the relationship between the components and the output of a system is unknown, as in our corporate governance problem, standard classification techniques, based on the machine learning (ML) paradigm could be employed to derive an approximate model [40, 83]. The most commonly used techniques in the reliability context are: neural networks (NN) [39], support vector machines (SVM) [40], Decision Trees (DT) [41-42], and Logic Learning Machine (LLM) [43], among others.

ML techniques have been used in many real situations such as to classify operation anomalies in nuclear systems [84], to detect important factors in multi-criteria decision model [79], to derive surrogate models to speed-up Monte Carlo simulations [40, 83], to perform pump failure rate analysis [41], to name a few. In [36, 42, 46], ML techniques were used to derive the *SF* of a general system, modelled as a network.

The basic idea when using any ML technique is: a set of different states of the system along with the components states (the training set) is examined by the selected technique in order to assess whether a proposed analytical expression can be used to adequately mimic the behaviour of the system.

In some approaches (e.g., NN or SVM) the analytical expression of the operation derived generally includes non-linear terms (or operators), whose meaning is difficult to interpret. Other approaches are based on rule generation methods or rule learners [44] (e.g., DT, LLM), that is, techniques that produce a set of logical rules that describes the binary function *SF*. In general, the rules have the well-known **if-then-else** structure. For example: **if** $(x_i = 1)$ **then** y=1 (the system is operating) **else** y=0 (the system is failed). In any case, the models derived properly mimic the system output, given the states of the input variables.

In this paper we consider the use of rule learners that allows an easy interpretation of the results as well as a fast reliability assessment of a company governance system and company characteristics.

3.2.2 Decision tree

A DT produces a set of conjunctive decision rules. In this format, there are only "**AND**"s within each rule, but each rule exists within an **if-then-else** structure. For example, consider the system shown in Figure 1. Using all of the possible states in the network (i.e., 2^4 =16) and determining the system output by inspection (shown in Table 3, i.e., the training set), the DT presented in Figure 2 is derived [36].

Table 3
Component and system states for the network shown in Figure 1

Figure 2
Example of a decision tree [36]

To determine if a selected network configuration is operating or not, its components' states are analysed. First, the DT verifies the state of component 2 (x_2): if x_2 = 1 (i.e., operating) then the DT selects the right branch and verifies the state of component 4 (x_4). If component 4 is failed (i.e., x_4 = 0), the left branch is selected and a final conclusion is derived: the system is failed (y=0). On the other hand, if component 4 is operating (i.e., x_4 = 1), the right branch is selected and it is concluded that the system is operating. A similar procedure is defined in the case that the first test related to the component 2 concludes that component 2 is failed.

The structure of a binary DT corresponds to a direct acyclic graph. Each node corresponds to a decision node with links to other nodes or a leaf node. At any decision node, a test on the state of a specific component is performed, while any leaf node represents the state of the system [45]. This special structure allows extracting different rules to be able to conclude the state of the system by following the paths from the starting node (the root) to any leaf node: "Every node encountered produces a condition to be added to the **if** part of the rule; the final leaf contains the output value to be selected when all the conditions in the **if** part are satisfied. Since the tree is a direct acyclic graph we have as many rules as leaves" [45]. For example, the following set of disjoint decision rules solves the problem in Figure 2:

if $x_1 = 0$ AND $x_2 = 0$ **then** $y = 0$
else if $x_1 = 0$ AND $x_4 = 0$ **then** $y = 0$
else if $x_2 = 0$ AND $x_3 = 0$ **then** $y = 0$
else if $x_3 = 0$ AND $x_4 = 0$ **then** $y = 0$
else $y = 1$

Other rule learner approaches (for example, LLM) produce a set of compact rules for each class. For the previous example, the LLM approach produces the following rules:

if (x_1=1 AND x_3=1) **then** $y = 1$;
if (x_2=1 AND x_4=1) **then** $y = 1$

which is equivalent to the *SF* for this network $SF(\boldsymbol{x}) = x_1x_3+x_2x_4$.

In general, LLM produces better results than DT does [46]. However, the *SF* derived is not in disjoint form. Hence, an additional transformation is required (e.g., the algorithm KDH88 [47]) to convert the *SF* to RE.

In many cases, the set of rules [46] derived are associated with special operators with a physical interpretation. For example, the set of rules for the class failed could correspond to the set of min-cuts or min-paths [86-89, 91].

3.2.2 Approximating the SF

In real cases, the training set could not be completely derived by inspection since there are many system states to be analysed, the conditions for operation are not evident, or, as in the corporate governance problem, the information is limited. In these cases, classification techniques are only able to extract an approximation of the *SF* of a system and, consequently only an approximated RE (ARE). In general, the approximation of the *SF* to the real one is better as long as the samples in the training set increase.

In order to apply a classification method to generate the *SF*, the set of all of pairs ($\boldsymbol{x}_i$, y_i) (representing different components and system states) is organised in two subsets to be used in the training phase and in the subsequent performance evaluation of the resulting set of rules. To this end, N_T+N_E pairs ($\boldsymbol{x}_i$,y_i) have been randomly assigned to each subset. The first N_T pairs are then used to form the training set, whereas the remaining N_E pairs are employed to evaluate the performance of the classifier, according to the standard measure of *sensitivity, specificity* and *accuracy* [61]:

$$sentivity = \frac{\mathrm{TP}}{\mathrm{TP+FN}}\ ;\ specifity = \frac{\mathrm{TN}}{\mathrm{TN+FP}};\ accuracy = \frac{\mathrm{TP+TN}}{\mathrm{TP+TN+FN+FP}}$$

where

- TP (respectively, TN) is the number of examples belonging to the class y = 1 (respectively y = 0) for which the classifier gives the correct output,
- FP (respectively, FN) is the number of examples belonging to the class y = 1 (respectively y = 0) for which the classifier gives the wrong output.

For reliability assessment, *sensitivity* and *specificity* give the percentage of correctly classified operational states and correctly classified failed states, respectively.

Although the performance of the selected technique is an important aspect to be considered, it is also important that the classifier derived has the ability to comply with technical aspects observed in the real system [36, 39-42].

4. The proposed mapping

In this section we describe how the corporate governance assessment is mapped into a reliability model.

Table 4 shows a hypothetical set of 19 companies in a given year and country (i.e., the system), and three particular input variables or components associated with board structure, coded as binary variables. The complete set of input variables to be used is described in section 5. For example: i) *bs_poly_r* = 1 means that a company has a policy for maintaining a well-balanced membership of the board; ii) *bs_expe_r* = 0 means that companies lack disclosing the number of years, on average, how long each member has been on the board; and iii) *bs_noexe_r* =1 indicates that companies report the percentage of non-executive members belonging to the board.

The average ROA (*roa_mean1*) is selected as the system output ***y***. A *roa_mean1* =1 means that the system is in the operating state when a company is outperforming a reference value and *roa_mean1* =0 shows that the system is the failed state.

Table 4
Components and system states for a corporate governance system

The main idea of the proposed approach is to use a ML algorithm to extract an *SF* that mimics the behaviour of the corporate governance assessment (as described in 3.2.2).

This mapping to a reliability system gives a practical advantage for decision makers because:

1) It characterises the corporate governance components (operating or failure), enhances corporate transparency (disclosure and reporting) as a central aspect of the system reliability.
2) It evaluates under what corporate governance conditions and firm-specific circumstances the system is functioning.
3) The ARE derived could be used to numerically estimate the probability of system functioning as well as component importance indices.

5. Case study

5.1. Data section

The case study for mapping the corporate governance assessment to reliability systems uses a dataset from 1,203 U.S. listed companies during the period from 2002 to 2014. The financial information is obtained from Reuters Datastream™ and Thomson One™, and the non-financial information is from the ASSET4 ESG module in Datastream. Companies are classified according to the data providers in ten economic sectors based on the International Standard Industrial Classification (ISIC). Finally, after correcting the dataset from some data anomalies (e.g., missing data, blanks, duplicates, non-available "NA"), the original panel of 15,639 company-year observations were reduced to 8,412 observations on 1,109 companies after the data cleaning (see Table 5).

Table 5
Sample size and classification

5.2. Corporate governance components

The segment ASSET4 ESG in Datastream identifies 33 corporate governance components that companies need to disclose and report. These components belong to five corporate governance perspectives: board structure, board function, compensation policy, shareholder rights, and vision and strategy.

Table 6 shows the meaning of their states in the form of operating "1" and failure "0". These binary values come from the evaluation of the data provided by Datastream, and also follow the best corporate governance practices in terms of disclosure and transparency [1, 48].

Table 6.
Corporate governance components

Finally, some data adjustments were also considered regarding data anomalies in order to characterise the component states. For example, a component recorded as "NA" is considered in the failed state.

5.3. System output y (firm performance)

Several empirical studies investigating into corporate governance and firm performance have tended to focus on specific governance components such as board structure, ownership, board function and duality [14, 18, 49-52]. These studies suggest that return on assets (ROA) is a central aspect to link corporate governance components to firm performance and hence will be considered as the system output in our model.

ROA, the ratio of earnings before interest, taxes, depreciation and amortization to total assets, measures how efficient managers are using the company's resources to generate profits [7, 14, 18, 49-52]. Thereupon, to map this information into the proposed system approach, the variable *roa_mean1*, for a given year, is defined as 1 if the system is operating in this state (i.e., a firm's ROA is outperforming the industry), 0 otherwise.

5.4. Company-specific characteristics (other system conditions)

Previous econometric approaches have stated that firm-specific conditions also affect firm performance. For example, companies' age [49, 52, 56], number of business segments [52], debt structure [49, 52, 57], size [56, 58], growth opportunities [59-60], and firm risk [7, 52] are among the firm-specific conditions.

Based on such works, the reliability systems approach presented in this paper takes into consideration also firm-specific conditions in order to illustrate their potential influences on the system output. These specific conditions are explained as follows:

- Debt (*ltdebtasset_mean1*): this is the ratio of the company's long-term debt to total assets adjusted by the industry information form Datastream. For example, a company's debt ratio above the industry takes a value of 1 (overleveraged), 0 otherwise.
- Size (*mv_mean1*): it takes into account market value of equity of a company adjusted by the industry information form Datastream. Thus, firm value above mean company value for the industry takes a value of 1, 0 otherwise.
- Growth opportunities (*mtb_mean1*): this is the market-to-book ratio of a company, which is a proxy for growth opportunities associated with companies. This ratio is also adjusted by the industry information from Datastream: the ratio of the firm above the mean value for the industry takes a value of 1, 0 otherwise.
- Risk or stock price volatility (*nvolreturn_mean1*): it is computed from the monthly company return index (RI in Datastream) using the standard deviation of the past 12 months: the standard deviation of returns of a firm above the corresponding mean standard deviation for the industry takes a value of 1, 0 otherwise.
- Age (*comp_age)*: this element (categorical variable) takes into consideration both a company's foundation date and incorporation date and for those companies delisted, age is then adjusted appropriately. This information is found in Thomson One.
- Number of business segments (*numbusegm*): this measures the number of business segments (categorical variable) reported by each company at the end of the fiscal year. This information is also obtained from Thomson One.

The training set is selected with the 70% of the total pairs ($\boldsymbol{x}$, y) [62] and the rest of pairs are assigned to the testing data set. However, to avoid considering more samples in a class than in another, a set of 8,412 samples is selected with approximately 50% of each class, from the total pairs.

As previously mentioned, DT algorithms produce rules that are easily converted to RE. For this reason, we use a DT algorithm implemented in the WEKA environment [63-64]: namely the J48 algorithm [39, 65-66].

6. Results

6.1. Association rules and the Birnbaum index

The procedure J48 from Weka extracts a set of 246 rules with performance indices:

Training phase	**Testing phase**
Accuracy= 71.55%. TP= 64.3%; FP = 35.7% TN= 78.8%; FN= 21.2%	Accuracy= 83.32%. TP= 88.1%; FP = 11.9% TN= 79.4%; FN= 20.6%

A qualitative analysis of the rules reveals that 16 out of the 33 variables appear at least once in the set of rules. The number of conditions in a rule varies between 2 and 23.

Examples of some generated rules are as follows (highlighted terms correspond to components):

1) IF *mtb_mean1* = 0 AND *nvolreturn_mean1* = 0 AND ***bs_expe_r*** = 0 THEN *y*=0

2) IF *mtb_mean1* = 0 AND *nvolreturn_mean1* = 0 AND ***bs_expe_r*** =1 AND ***bf_inomcom_r*** = 0 AND ***bf_bmeet_r*** = 0 THEN y= 0

3) IF *mtb_mean1* = 0 AND *nvolreturn_mean1* = 0 AND ***bs_expe_r*** =1 AND ***bf_inomcom_r*** = 0 AND ***bf_bmeet_r*** =1 AND ***vstr_csrxaud_r*** = 0 AND *numbusegm* = 1 THEN y=1

4) IF *mtb_mean1* = 0 AND *nvolreturn_mean1* = 0 AND ***bs_expe_r*** =1 AND ***bf_inomcom_r*** = 0 AND ***bf_bmeet_r*** =1 AND ***vstr_csrxaud_r*** = 0 AND *numbusegm* > 1 THEN y=1

Note that, for a company with *mtb_mean1* = 0 and *nvolreturn_mean1* = 0, rule 1) corresponds to a first-order cut set.

As previously mentioned, all of the rules with the condition *y* =1 can be used to derive the ARE. For example, one of the terms associated with ARE, valid for companies with: *mtb_mean1* = 0 AND *nvolreturn_mean1* = 0 AND *numbusegm* = 1, is shown as below:

P(*bs_expe_r* =1)*P(*bf_inomcom_r* =0)*P(*f_bmeet_r* =1)*P(*vstr_csrxaud_r* =0)

where, for example, P(*bf_inomcom_r* =0) is the probability that component *bf_inomcom_r* is "failed": the company does not report the percentage of non-executive board members on the nomination committee.

The ARE can then be used to estimate the reliability of any selected company, that is, the probability that a selected company's ROA is outperforming its industry.

To illustrate, let's consider a company with the following characteristics: *numbusegm* = 2 and *comp_age* = 4. Let's further assume that for this company, the probability of failure of all of the components is 0.10 (noting that probability values could be estimated from yearly records of the company). Then, the numerical evaluation of the ARE results in a reliability level of almost 0.90 (0.8934). Note that, to the best of our knowledge, the likelihood of this corporate aspect is difficult to quantify using traditional approaches.

6.2. Model assessment

As previously mentioned, an important aspect that must be considered when using a surrogate model is its ability to comply with technical aspects observed in the real system. To illustrate this issue, first, we evaluated the importance of the components of the company with *numbusegm* =2 and *comp_age* =4, using the well-known Birnbaum reliability index (Figure 3). In this figure, a large index means that a small change in the reliability of a component will result in a comparatively large change in the system reliability ([38]).

Figure 3.

Birnbaum index of components for a company with *numbusegm* =2 and *comp_age* =4

The analysis of the Birnbaum index reveals that the reliability-mapping approach proposed is able to correctly mimic the behaviour of the system analysed. For example:

a) Figure 3 shows that the variable *mtb_mean1* (grow opportunities above the industry) is crucial for the reliability of the system. This aspect is aligned with the literature [59-60] because a high market-to-book ratio indicates how well managers are using a firm's resources to drive current and future performance as it reveals high expected future cash flows. For instance, using the cash holding on value increasing projects [67], enhancing R&D investment and speeding innovations [68] are among such aspects.
b) The Birnbaum index attributed to component "reporting corporate social responsibility" (*vstr_grcguid_r*) influences the well-functioning of the system relative to the other corporate governance mechanisms. Some authors [69-71] argue that engaging in socially responsible activities enhances firm performance; however, this depends on specific companies' supply and demand conditions [69]. Wang & Hsu [70] and Mishra & Suar [71] show that fulfilling corporate social responsibility would impact positively on firm performance.

c) The Birnbaum index for the component *bf_bmeetave_r* (reporting information associated with the average of board meetings) impacts on the trustworthiness of the company. This aspect has been studied in [72-73] but with inconclusive nexus with firm performance.

To provide a second test for assessing the strength of the model derived, let's consider that all of the probabilities of failure of the components could vary in [0.05, 0.15], *comp_age* = 4 and the number of business segments could vary (i.e., 4, 6, and 8). The uncertainties are modelled by uniform independent distributions and a simple Monte Carlo approach, based on 10,000 samples is used in the evaluation.

Figure 4 shows the minimum, average and maximum values for the reliability of the system. Note that the values are almost equal to one another, suggesting that the number of business segments under the scenarios simulated have no influence, as concluded in [52].

Figure 4.

Distribution the reliability for different number of business segments and *comp_age* = 4

Figure 5 shows the importance of the components on the reliability of the system, evaluated using the rank correlation index (RCI). The RCI is able to capture possible nonlinear effects among the components variability and the system output [74].

Figure 5.

Rank correlation index for different companies' business segments and *comp_age* = 4

As in the previous evaluation using the Birnbaum index, the action to improve the companies' growth opportunities (*mtb_mean1*) is the most important factor for affecting the reliability of the system. Again, the rest of the components have less important effects in the trustworthiness of the company. However, note that in this case, the component *vstr_grcguid_r*, for different companies' business segments is still the second most important component but with a greater potential influence than those observed in Figure 3. This aspect is aligned with the analysis of Wang & Hsu [70] and Mishra & Suar [71] regarding the role of social responsibility activities and firm performance.

6.3. Discussion

The results from mapping corporate governance components to a reliability model show that disclosure on a) compensation policy, b) remuneration and vesting options, and c) due reporting on independence of board function and board structure are central aspects for the operating state of the system. The results can also be considered as a complementary evidence of the role of transparency in corporate governance practices and mechanisms [15-16, 30] to study factors influencing firm performance using the theory of reliability system.

Compensation policy discloses whether the corporate governance practices are based on competitive and balanced management compensation not only to attract and retain executives and board members. Remuneration and vesting options show whether that compensation is linked to individual or company targets (financial or non-financial). Both aspects allow aligning the incentives of the managers while protecting the interests of the shareholders. Remarkable problems associated with compensation were uncovered during the recent financial crisis, which notably are related to excessive remuneration experienced by managers in the main largest banks in U.S and Europe, jeopardizing the global financial system.

Therefore, independence of board function and board structure show how well-balanced is the board of directors to have an independent decision-making process based upon their given responsibilities, commitment, and effectiveness to protect the firms value and shareholder interests.

The results can also be considered as a complementary evidence of the role of transparency in corporate governance practices and mechanisms [15-16, 30], which always reduces asymmetries of information, to study factors influencing firm performance. Finally note that the model derived could be easily used for:

I. Estimating the reliability of different types of companies (e.g., by altering the company age and the number business segments).
II. Assessing the effects on the reliability of the system when considering the uncertainty that may exist regarding the probabilities of failure of the components of the system.
III. Carrying out more detailed sensitivity studies for robustness (e.g., based on global sensitivity analysis [75]).
IV. Analysing other systems outputs (e.g., bankruptcy and valuations) and integrating other components (e.g., social and environmental attributes).

7. Conclusions

In this paper, a reliability system approach is proposed to successfully mimic a corporate governance framework. The basic idea is to consider corporate governance as a complex system, composed of inputs related to corporate governance practices and mechanisms about reporting and transparency (i.e., components) and outputs (i.e., system performance). The system is mapped into a reliability model, where operating/failed states of components and company-specific conditions are used to define the structure function, given a selected company performance. The structure function is approximated using machine learning techniques and easily converted into an approximated reliability expression that could be used to quantify the reliability of any selected company, that is the probability that a company is outperforming the industry. The results of the proposed approach are evaluated using accepted performance measures, and the extracted *SF* mimic the behavior of the corporate governance system, complying with a lot of theoretical aspects described in the literature.

The results of this paper not only show that growth opportunities matter for the proper functioning of the system but also suggest that if companies are more transparent (i.e., the probability of failure of specific components is low) both the trustworthiness of companies and the system reliability improve.

This novel approach, tested on a set of listed U.S. companies, reveals how a full transparency perspective (reporting and disclosure) enhances the reliability of the system and helps to evaluate how well companies are controlled and managed. Consequently, this mapping can be seen as a more practical way to classify companies operating according to the shareholders' interests, and to help them in the decision making process. Therefore, the board of directors can learn what corporate governance components are more pivotal for the most successful companies.

Future research is required to consider other aspects of regulation, mainly associated with the external corporate governance practices, and other company-specific information, which might affect the operating state of the system. For example, one can further consider how to compare different corporate governance systems across countries [76], assess, comply or explain practices [33], evaluate the impacts of large shareholder and investors [77], and analyse other system perspectives (e.g. company valuation, financial distress, corporate bankruptcy, social and environmental responsibility of corporations, and company suitability).

Therefore, the research questions could also resort to additional models (e.g., multistate models [78, 106]) and signature function or the survival signature [85] in reliability modelling, data mining approaches [39], robustness analysis [79], multi-criteria methods [80-81]), as well as the result comparisons with traditional empirical regression models [7, 14, 52, 82].

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List of Tables:

Table 1
Corporate governance as a system approach

Authors	**Observations and perspectives**
Lipton & Lorsch [22]	The cornerstone of the corporate governance system is the board of directors, which legitimates both actions taken and decisions made by managers in the name of the shareholders. Thus, the system should be able to produce meaningful information about the board of directors, company performance, and its managerial leadership.
Holmstrom & Kaplan [23]	One of the major risks for the corporate governance systems, especially in U.S, is overregulation, which can be costly and counterproductive for companies. However, because of many corporate governance scandals, Sarbanes-Oxley Act of 2002 has helped to renovate confidence in the U.S. corporate governance system, and these authors consider that a less effective system leads to poor company productivity and performance. However, it is important to assess executive compensation, shareholders' interests, and the board of directors' decisions.
Strine [24]	A rational corporate governance system should rely more on accountability, abandoning some unnecessary staggered or classified board, implementing clearer corporate elections, and controlling managerial compensation, without forgetting that companies should generate benefits for both shareholders and stakeholders (employees, communities, for example).
Mason & Simmons [12]	A corporate governance system has faith in the board of directors, who defines and exercises corporate strategies according to the key beneficiaries' interests. For instance, one element into the systems is corporate social responsibility. It helps business as a linkage between companies' outcomes and stakeholders' viewpoints.
García-Castro et al. [25]	Corporate governance is perceived as an insider system (shareholder-oriented), mainly because the governance practices and mechanisms are noticeably interrelated with different firm perspectives (e.g., firm performance, value creation)
Bellavite Pellegrini et al. [26]	Corporate governance systems are observed from a separation perspective. Indeed, they consider the implications of the separation between managerial and supervisory bodies. For instance, in a one-tier system the board of directors and the supervisory board work together; and in a two-tier system both boards work separately.
Aguilera & Crespi-Cladera [11]	These authors state that governance can be represented as a leadership system, with practices of managerial control, and norms and mechanisms that shape how companies are addressed and governed in the best interest of the shareholders.

Table 2
Transparency (reporting and disclosure) into a corporate governance system

Authors	Comments and perspectives
Adiloglu & Vuran [30]	Corporate governance is a way to enhance transparency of the relationships between the shareholders, board of directors and managers in terms of roles and obligations to create sustainable value for all stakeholders. When companies are more transparent and information is accountable, investors' confidence improves. Transparency is one of the ground aspects of a corporate governance system.
Chen et al. [31]	Poor reporting and disclosure create asymmetries of information for investors and produce large economic costs. Transparency helps shareholders to understand more thoroughly about a firm's management and reputation and their impacts on performance (i.e., liquidity).
Cormier et al. [15]	Reporting and disclosure are central aspects of a firm's governance configuration, showing that boards are effective enforcing the corporate governance mechanisms and reducing the monitoring costs incurred by investors. Reporting corporate governance information (practices and mechanisms) is less costly than making market participants to gather it.
Hermalin & Weisbach [32]	Disclosing corporate governance information is a good practice that reduces managerial fraud or theft, which is mostly stimulated by regulators and public scrutiny due to many corporate scandals reported (i.e., bankruptcies, market manipulations) that have affected shareholders.
Luo & Salterio [33]	Divulging corporate governance practices allows market participants not only to evaluate whether companies are managed effectively but also to make informed decisions (i.e., buy companies' shares). Although disclosing can be mandatory or recommendatory, corporate governance depends mainly on their firm-specific characteristics.
Mahr et al. [16]	Under efficient information, the agency costs for firms with bad governance are higher than for those with good governance. Hence, shareholders are able to pay a higher price for the better-governed companies because of the reduction in monitoring and auditing costs.
Samaha et al. [34]	Disclosing corporate governance practices uncovers companies' strengths and weaknesses in performance, uncertainties, ownership dispersion, human resources capabilities, and so forth. Consequently, corporate governance disclosure can be associated with many attributes (i.e., board function and composition, board size, CEO duality, ownership and audit committee) that investors monitor in order to see how companies are addressed.

Table 3

Component and system states for the network shown in Figure 1

x_1	x_2	x_3	x_4	$y = SF(\boldsymbol{x})$
0	0	0	0	0
0	0	0	1	0
0	0	1	0	0
0	0	1	1	0
0	1	0	0	0
0	1	0	1	1
0	1	1	0	0
0	1	1	1	1
1	0	0	0	0
1	0	0	1	0
1	0	1	0	1
1	0	1	1	1
1	1	0	0	0
1	1	0	1	1
1	1	1	0	1
1	1	1	1	1

Table 4

Components and system states for a corporate governance system

Companies	x_1**= bs_poly_r**	x_2**= bs_expe_r**	x_3**= bs_noexe_r**	y **= roa_mean1**
Comp01	1	1	1	1
Comp02	1	1	1	0
Comp03	0	0	1	0
Comp04	1	1	1	1
Comp05	1	1	1	1
Comp06	1	1	1	0
Comp07	1	1	1	1
Comp08	0	1	1	0
Comp09	1	1	1	0
Comp10	1	1	1	1
Comp11	1	1	0	1
Comp12	1	1	1	0
Comp13	1	1	1	1
Comp14	1	1	1	0
Comp15	1	1	1	0
Comp16	1	1	1	1
Comp17	1	1	1	0
Comp18	1	1	1	0
Comp19	1	1	1	1

Table 5
Sample size and classification

Sectors-Years	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Basic Materials	25	24	31	38	37	39	46	59	58	59	58	52	31	557
Consumer Cyclicals	51	51	68	84	88	89	119	130	142	149	141	118	93	1323
Consumer Non-Cyclicals	64	63	75	87	88	93	111	115	114	113	110	82	54	1169
Energy	24	24	45	46	46	51	67	70	67	66	66	56	47	675
Financials	29	32	65	82	80	82	118	130	130	140	133	78	48	1147
Healthcare	32	34	50	53	48	49	59	68	68	67	65	49	33	675
Industrials	47	49	66	72	70	74	111	129	130	129	124	106	78	1185
Technology	46	49	62	73	69	76	87	110	113	114	107	79	65	1050
Telecom. Services	8	8	10	8	9	9	14	15	15	14	13	7	5	135
Utilities	25	25	33	35	37	39	48	57	55	48	48	33	13	496
Total	*351*	*359*	*505*	*578*	*572*	*601*	*780*	*883*	*892*	*899*	*865*	*660*	*467*	*8412*

Table 6
Corporate governance components

Perspectives	Components x_i	Definition (Operating "1", Failure "0")
A. Board Structure: It shows how well-balanced the board of directors is into the corporate governance system.	1. bs_poly_r	Does a firm have a proper balance and diligence in the membership of the board? Y=1; N=0
	2. bs_expe_r	Does the company report the number of years (average) each member has been on the board? Y=1; N=0
	3. bs_noexe_r	Does the company disclose the percentage of (%) non-executive board members in the board? Y=1; N=0
	4. bs_indep_r	Does the company report the % of independent board members? Y=1; N=0
	5. bs_duality_r	Does the company report information about CEO-Chairman separation? Y=1, N=0
	6. bs_skills_r	Does the company report either the skills of every board member, the age of individual board members? Y = 1, N = 0
	7. bs_size_r	Does the company report the total number of members in the board at the end of the fiscal period? Y = 1, N = 0
	8. bs_divers_r	Does the company report the % of women in the board? Y=1, N=0
B. Board function: It measures the boards' and committees' role for managerial alignment and company control.	9. bf_iaudit_r	Does the company disclose, for the audit committee, % of the independent board members according to the firm stipulations? Y = 1, N = 0
	10. bf_imaudit_r	Does the company report, for the audit committee, % of the non-executive board members according to the firm stipulations? Y = 1, N = 0
	11. bf_audexp_r	Within the meaning of SOX for the audit committee, does the firm have at least three members and at least one "financial expert"? Y=1, N=0
	12. bf_icomcom_r	Regarding the compensation committee, does the company disclose % of the independent board members according to the firm stipulations? Y=1, N=0
	13. bf_imcomcom_r	Regarding the compensation committee, does the company disclose % of the non-executive board members according to the firm stipulations? Y=1, N=0
	14. bf_inomcom_r	Does the company report % of the non-executive board members on the nomination committee? Y=1, N=0
	15. bf_imnoncom_r	Regarding the nomination committee, does the company disclose % of the non-executive board members according to the firm stipulations? Y=1, N=0
	16. bf_bmeet_r	Does the company report the number of board meetings? Y=1, N=0
	17. bf_bmeetave_r	Does the company disclose the overall attendance (in percentage) of board meetings according to the firm stipulations? Y=1, N=0
C. Compensation policy: It measures competitive compensation for executives and board members according to specific firms' targets	18. cpoly_com_r	Does the company have a policy for performance-oriented compensation that attracts and retain senior executives and board members? Y=1, N=0
	19. cpoly_rem_r	Does the company disclose the highest remuneration package? Y=1, N=0
	20. cpoly_brem_r	Does the company disclose the total board member compensation of the non-executive board? Y=1, N=0
	21. cpoly_stok_r	According to the firm's statutes or by-laws, do firms require that stock-options being contracted with a vote at a stockholder meeting? Y=1, N=0
	22. cpoly_ltcom_r	Does the company report the maximum time horizon of targets to reach full senior executives' compensation? Y=1, N=0
	23. cpoly_vest_r	Does the company report the number of years that most recently granted stock options or restrict stocks (since the granted date)? Y=1, N=0
D. Shareholder Rights: It considers both equal treatment of shareholders and preventing the usage of anti-takeover devices.	24. shrt_poly_r	Does the company have a policy to treat equally shareholders (large and minority) or limit the usage of anti-takeover devices? Y=1, N=0
	25. shrt_votrt_r	Are all shares of the company providing equal voting rights? Y=1, N=0
	26. shrt_own_r	Regarding ownership, is the firm owned by a shareholder with majority of the voting rights, including veto of power? Y=0, N=1
	27. shrt_clabs_r	Does the company have a classified board structure? Y=0, N=1.
	28. shrt_stabs_r	Does the company have a staggered board structure? Y=0, N=1.
E. Vision and strategy: It evaluates management commitment to integrate financial and non-financial aspects into the daily operations.	29. vstr_chall_r	Reporting information, is the company acknowledging openly the opportunities and difficulties of integrating financial and nonfinancial issues? Y=1, N=0
	30. vstr_csr_r	Does the company have a corporate social responsibility (CSR) committee or team? Y=1, N=0
	31. vstr_grcguid_r	Is the CSR report published according the Global Reporting Initiatives (GRI) guidelines? Y=1, N=0
	32. vstr_csrrep_r	Does the company's extra-financial report consider also its global activities? Y=1, N=0
	33. vstr_csrxaud_r	Does the company consider an external auditor for its health & safety, social responsibility, and sustainability report? Y=1, N=0

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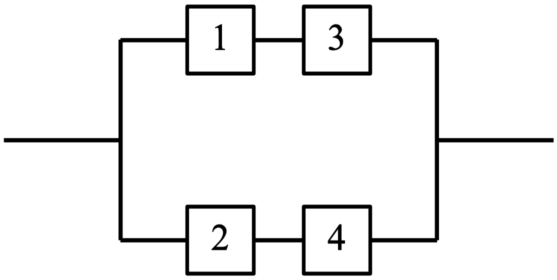

Figure 1. A four-component network [36]

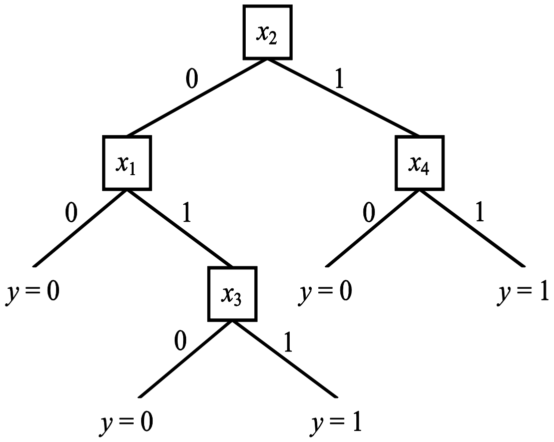

Figure 2. Example of a decision tree [36]

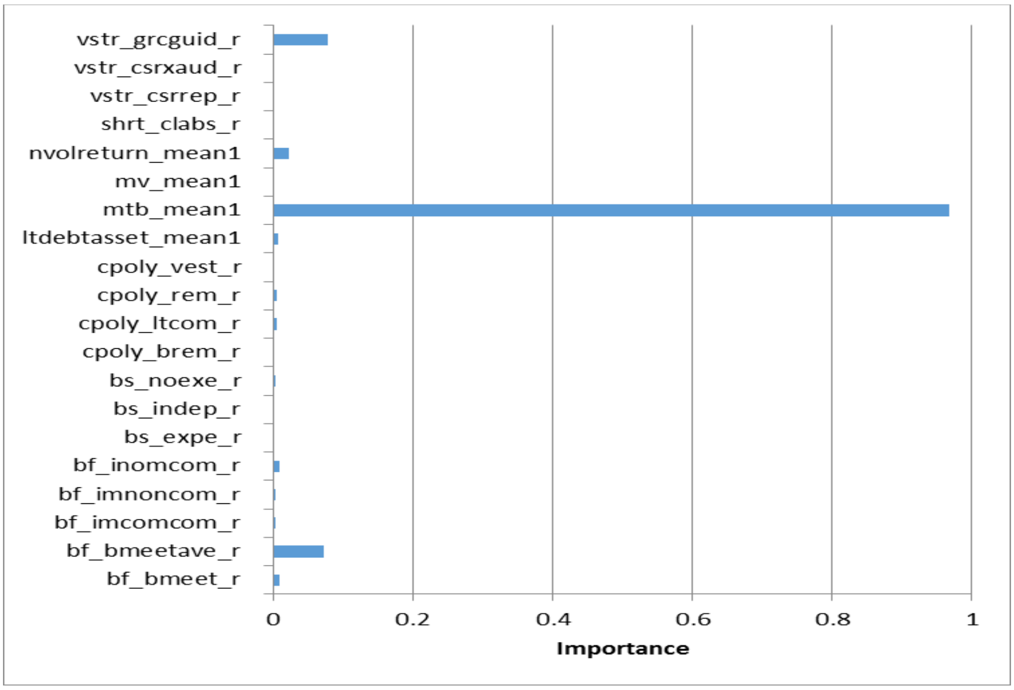

Figure 3. Birnbaum index of components for a company with numbusegm =2 and comp_age =4

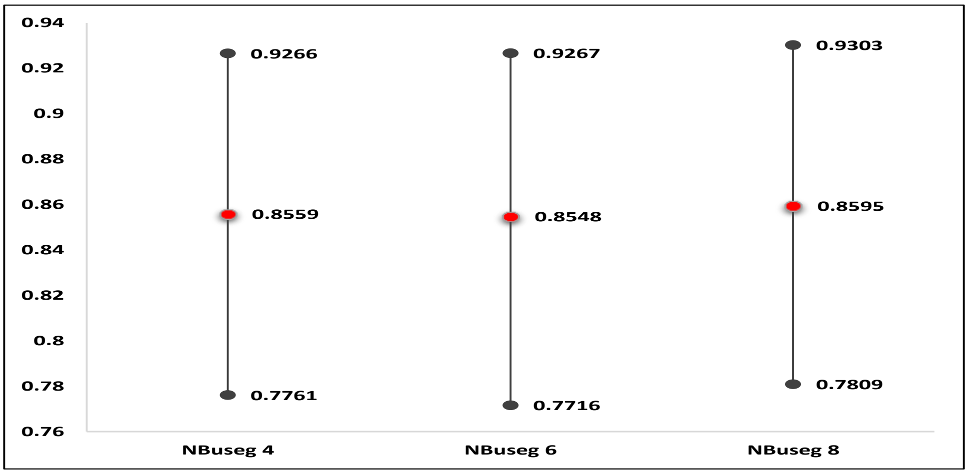

Figure 4. Distribution the reliability for different number of business segments and comp_age = 4

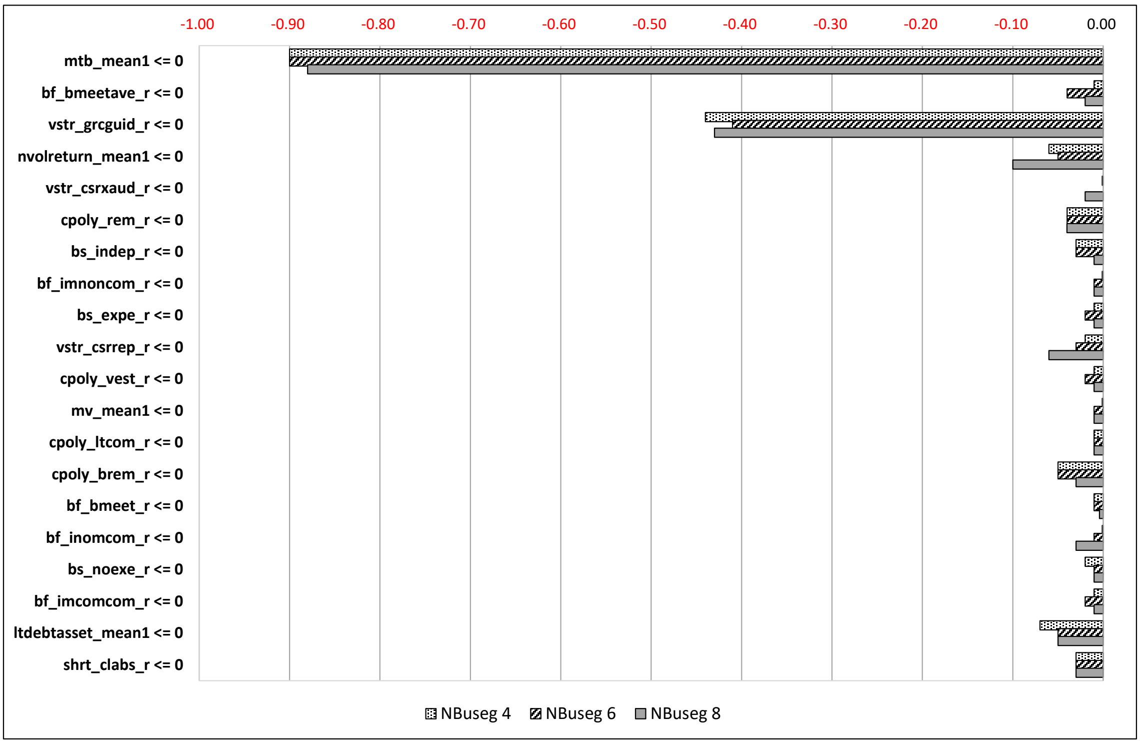

Figure 5. Rank correlation index for different companies' business segments and comp_age = 4