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Process reliability as an effect of variability reduction: the role of quality and organisational culture

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Abstract: The aim of this article is to identify the relationships between quality management, organisational culture maturity, and process reliability, as well as to determine their significance for the economic efficiency of companies in the raw materials sector. It is assumed that economic efficiency results from process stability, which is conditioned by an organisation's ability to reduce operational variability. The study is based on an integrative approach combining the process perspective, quality management, and organisational culture theory. The research is qualitative in nature and includes a structured literature review (Scopus, 2016–2026) and an analysis of annual reports of companies from the mining and energy sectors. The results indicate that quality management serves as a mechanism for reducing process variability, the effectiveness of which depends on the maturity of the organisational culture. Organisational culture influences data quality, deviation reporting, and the organisation's ability to learn. At the same time, the development of the Quality 4.0 concept confirms that digital tools require stable processes and a mature organisational context. As a result, a relationship model is proposed in which the maturity of the organisational culture determines the effectiveness of the quality management, leading to reduced variability, increased process reliability, and improved predictability and economic efficiency. The contribution of the article lies in integrating three perspectives that are often considered separately – quality, organisational culture, and process reliability – by embedding them in the context of extraction processes and the challenges of sectoral transformation.

Keywords: quality management, organisational culture, process reliability, process variability, mining, energy sector, economic efficiency

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1. Introduction

Contemporary mining is undergoing a phase of intensive transformation driven by economic, environmental, and social conditions. Increasing pressure for operational efficiency, workplace safety, and reduced environmental impact is leading to changes in the management of production processes. These changes involve not only the implementation of new technologies but also a redefinition of approaches to quality management and organisational culture.

Under conditions of growing complexity in technical and organisational systems, process variability becomes a key challenge, representing a significant source of operational disruptions and decreased reliability. Its reduction is essential for ensuring the stability and predictability of enterprise performance. In this context, quality management serves as a mechanism for limiting variability, while organisational culture influences deviation identification, data quality, and the organisation's capacity for learning.

The extraction process is carried out under conditions of high geological variability, complex operational interdependencies, and time–cost pressure, making uncertainty an inherent feature of the system. In such conditions, increasing efficiency without stabilising the process leads to greater risk and hidden costs. This implies that economic efficiency does not arise solely from financial parameters but is fundamentally rooted in process stability.

Despite the growing body of research on quality management, organisational culture, and process reliability, these issues remain fragmented and are rarely addressed in an integrated manner (Deming, 2018; Juran, 1989). The bibliography lacks an approach that combines these three perspectives in the context of extraction processes and their impact on economic efficiency.

The aim of this article is to identify the relationships between organisational culture maturity, quality management, and process reliability, as well as to develop an explanatory mechanism linking these elements through variability reduction. The paper adopts the thesis that the economic efficiency of a mining enterprise results from process reliability, which is a function of quality management and the maturity of the organisational culture.

2. Research methodology

The study is qualitative and exploratory in nature, aiming to identify the relationships between quality management, organisational culture, and process reliability under conditions of high operational variability. An approach integrating literature analysis with secondary data analysis was applied, enabling the combination of a theoretical perspective with the observation of organisational practices.

2.1. Literature search and selection procedure

The literature review was conducted in a structured manner using the Scopus database (11 April 2026). The search covered publications from 2016 to 2026 addressing the relationships between process reliability, quality management, organisational culture, and process variability in an industrial context, with particular emphasis on mining.

The application of filters (document type and subject areas) reduced the initial set of results from 2,444 to 848 publications. The next screening stage was based on an analysis of titles, abstracts, and keywords, and resulted in a final set of 40 records selected for detailed analysis. The purpose of this stage was not to conduct a bibliometric review, but to identify studies that directly supported the construction of the conceptual framework linking quality management, organisational culture, process variability, reliability, and economic efficiency.

The inclusion criteria were as follows: publications indexed in Scopus; publications from 2016 to 2026; English-language journal articles and conference papers; studies addressing quality management, process improvement, organisational culture, process reliability, process variability, operational stability, or economic efficiency; and studies referring to industrial, mining, energy, or other high-variability operational contexts.

The exclusion criteria included publications only loosely related to the research problem, studies focused exclusively on technical reliability without reference to quality management or organisational factors, publications concerning contexts unrelated to industrial process variability, and papers that did not explicitly contribute to explaining the relationship between quality, culture, variability, reliability, or operational performance. The reduction from 848 to 40 records was therefore based on the relevance of each publication to the key elements of the proposed model and to the research gap identified in the article.

Based on this, the main research streams were identified and are synthetically presented in Tab. 1.

Tab. 1. Main research areas and their contribution to the analysis of relationships between quality, organisational culture, and process efficiency

Area	Main contribution	Key publications
Quality management and process improvement	Quality and continuous improvement enhance organisational stability and performance.	Patel & Patel, 2021; Antony et al., 2017; Sahoo, 2019
Organisational culture and soft factors	The effectiveness of quality depends on culture, engagement, and behaviour.	Abushaikha et al., 2025; Aleu & Van Aken, 2016; Arcidiacono et al., 2025
Digitalisation, Quality 4.0, and analytics	Digital tools strengthen quality but require data and process maturity.	Dias et al., 2022; Yadav et al., 2021; Maheshwari & Devi, 2024; Omar et al., 2019
Procedures, reliability, and risk	The quality of procedures and maintenance affects reliability and safety.	Johnson et al., 2025; Orošnjak et al., 2025
Transformation and process efficiency	The integration of quality and operational efficiency strengthens organisational resilience.	Pierli et al., 2026; Seth et al., 2016

Source: own elaboration based on the Scopus database

The analysis indicates that the literature provides a strong description of individual elements of the problem; however, it rarely presents them as a coherent mechanism linking organisational maturity to process stability and efficiency. The identified gap constitutes a starting point for further considerations.

2.2. Analysis of organisational practices based on company reports

The second component of the study involved an analysis of annual reports from companies in the raw materials and energy sector: KGHM Polska Miedź S.A.,

TAURON Polska Energia S.A., ORLEN S.A., and Lubelski Węgiel Bogdanka S.A. The sample selection was purposive rather than statistically representative. The companies were selected because they are large and strategically important entities in the Polish raw materials and energy sector, operate under conditions of high operational complexity and exposure to process variability, and are subject to strong regulatory, environmental, and cost pressures. An additional criterion was the availability of extensive annual and management reports for 2024, including information on risk management, operational performance, safety, organisational culture, and ESG-related issues.

The choice of cases was therefore guided by analytical and theoretical relevance. The selected companies provide a suitable basis for examining how quality management, organisational culture, and management systems are reflected in the reporting of operational stability in organisations exposed to high variability and uncertainty.

The study was conducted using qualitative content analysis, focusing on four areas:

1. quality management and process improvement;
2. identification and reporting of operational deviations;
3. elements of organisational culture;
4. indirect indicators of operational stability.

The unit of analysis was a thematic text fragment, most often a paragraph, subsection, or clearly separated part of a report referring to one of the analytical areas. The coding was conducted using a predefined coding framework corresponding to the four categories listed above. Each identified fragment was assigned to the category that best reflected its dominant meaning in the context of the research question.

To reduce interpretative bias, the coded fragments were repeatedly checked against the analytical categories and compared across the analysed companies. Ambiguous classifications were discussed by the authors until a consistent interpretation was reached. This procedure was intended to ensure interpretative coherence appropriate for an exploratory qualitative content analysis based on secondary data.

Due to the lack of direct measures of process variability in the analysed reports, an indirect approach was adopted. Managerial and operational data were interpreted as manifestations of process stability or instability when they referred to the repeatability of production and sales results, changes in cost levels and cost structures, operational disruptions, business continuity, risk mitigation mechanisms, control systems, or the ability to maintain stable performance under variable environmental, geological, technological, or market conditions.

The analysis was comparative in nature and enabled the identification of patterns and differences in companies' approaches to quality management, risk management, and process organisation, with particular emphasis on the degree of integration of these areas and their impact on operational efficiency.

3. Literature review and theoretical background

The literature review presented in the methodology section provides the foundation for an in-depth analysis of the relationships between process reliability, quality management, and organisational culture. This section synthesises the key research streams and further develops them towards a coherent framework of the problem.

Particular attention is given to the relationships between process variability, the mechanisms for its reduction, and their implications for operational efficiency and process reliability in highly complex organisations, including those in the mining sector.

3.1. Reliability as an economic category

Process reliability is not solely a technical category. Process instability leads to variability in production and costs, as well as increased uncertainty in forecasts and decision-making risk (Fig. 1). Therefore, reliability can be treated as an economic category, representing the interface between process engineering and controlling. This perspective is consistent with the classical understanding of quality as the ability to reduce variability and predict outcomes (Deming, 2018).

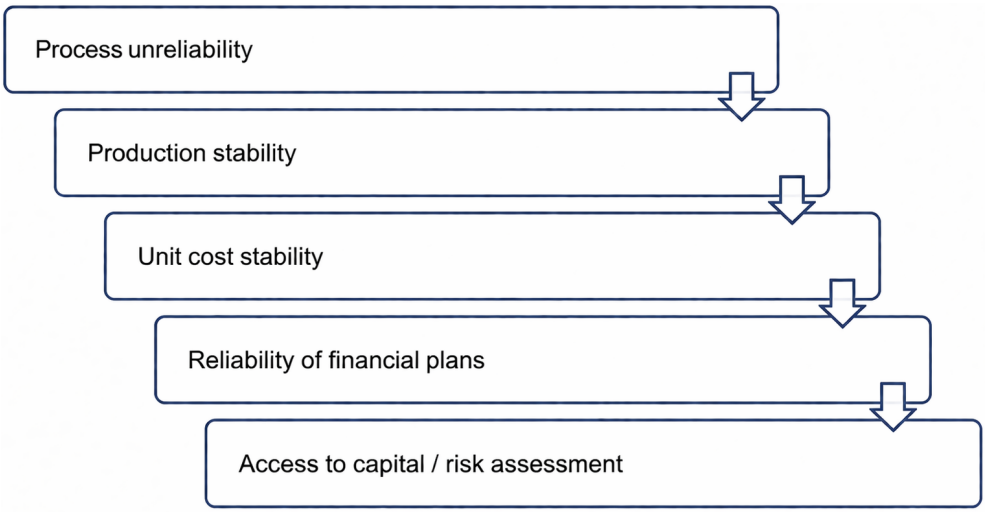

Fig. 1. Economic dimension of reliability

The literature emphasises that improving the quality of procedures and reducing operational errors are key mechanisms for enhancing the reliability of industrial systems (Johnson et al., 2025). Reliability can be measured, among other indicators, by the number of downtime events, the time between failures, deviations from the production plan, and production variability. However, the consequences of unreliability are primarily economic and are reflected in increased costs, lost revenue, and reduced quality of managerial information.

From a process perspective, this implies that improving organisational performance requires not only reacting to disruptions but, above all, stabilising process flows (Davenport, 1993).

3.2. Quality management as a mechanism for controlling variability

Quality management encompasses the identification and mapping of processes, their standardisation, the measurement of operational parameters, the analysis of deviations, and continuous improvement. From this perspective, it functions as a mechanism for reducing process variability, which is consistent with both Deming's (2018) and Juran's (1989) approaches.

The literature indicates that approaches such as Lean, Six Sigma, and TQM constitute the foundation for improving process stability and operational efficiency (Antony et al., 2017; Patel & Patel, 2021; Sahoo, 2019). At the same time, it is emphasised that the effectiveness of quality management depends not only on the

tools applied but also on the organisational context, including the level of process and managerial maturity (Aleu & Van Aken, 2016).

An important aspect is the dependence of quality management on the quality of operational data. The effectiveness of deviation identification and improvement actions is based on reliable information about process performance. When such information is distorted, quality mechanisms lose their controlling function and become merely formal in nature. This highlights the need to link quality management with organisational culture, which shapes the conditions for observing and evaluating processes.

3.3. Organisational culture maturity

Organisational culture constitutes a set of values, norms, and assumptions that shape employee behaviour and the way an organisation functions. According to Schein, it has a multi-level structure encompassing artifacts, values, and basic underlying assumptions (Schein & Schein, 2017).

In industrial enterprises, particular importance is attributed to safety culture and the culture of reporting deviations, both of which influence the quality of operational data and the ability to identify sources of variability. Studies indicate that factors such as leadership, employee engagement, and openness to error reporting determine the effectiveness of quality-related activities (Abushaikha et al., 2025).

The importance of organisational culture is also evident in the context of implementing the Quality 4.0 concept, which integrates digital tools, data analytics, and artificial intelligence with classical process improvement methods (Dias et al., 2022). At the same time, the effectiveness of these solutions depends on the data quality and process stability, which implies that digital technologies reinforce existing management systems but do not replace their foundations (Yadav et al., 2021).

3.4. Organisational culture maturity as a determinant of process variability

Organisational culture influences process variability by shaping operational behaviours, decision-making practices, and the quality of the data used in management. From this perspective, it acts as a moderating factor that strengthens or weakens the impact of quality management on process variability.

In organisations with a high level of cultural maturity, quality practices lead to a genuine reduction in variability. In contrast, in organisations with low maturity, they tend to become formalised, which limits their effectiveness. Of particular importance is the issue of information distortions (reporting bias), resulting from low levels of trust and limited openness to reporting deviations.

Thus, organisational culture affects not only the course of processes but also the quality of the measurement system and the organisation's ability to identify variability. In this sense, it can be interpreted as a 'variability filter', determining the effectiveness of quality mechanisms and the ability to achieve stable and predictable operational outcomes (Fig. 2).

Fig. 2 illustrates the mechanism through which organisational culture influences process variability via quality management. Organisational culture acts as a moderating factor, affecting the effectiveness of quality-related activities through the level of trust, willingness to report deviations, data orientation, and the organisation's capacity for learning.

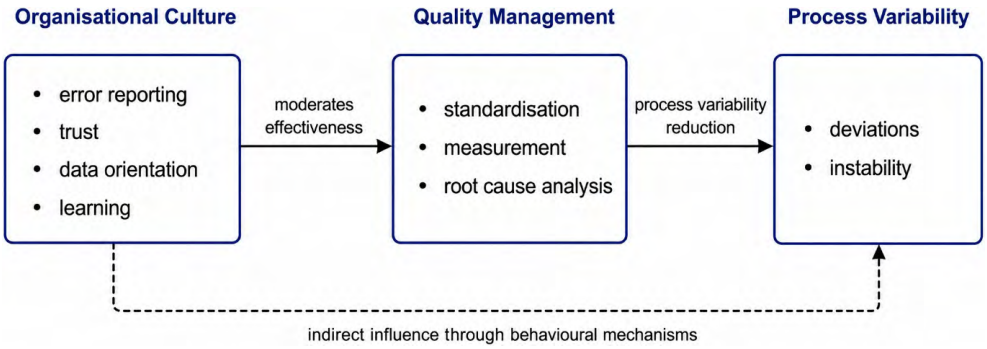

Fig. 2. Mechanism of the influence of organisational culture on process variability

Quality management – implemented through standardisation, measurement, and root cause analysis – serves as a mechanism for reducing process variability, the effectiveness of which depends on data quality and organisational conditions.

4. Literature synthesis and research gap

The approaches presented in the literature clearly indicate the importance of quality management as a mechanism for reducing process variability and improving operational efficiency. At the same time, the role of organisational factors, particularly organisational culture, in shaping the effectiveness of implemented quality solutions is emphasised. Despite the extensive body of research, the individual elements of this framework – quality, variability, reliability, and efficiency – are most often analysed separately or with limited interconnections.

The bibliography rarely attempts to integrate these elements into a coherent explanatory mechanism that clarifies how quality management, embedded in a specific organisational context, translates into process stability and economic outcomes. In particular, the role of organisational culture as a moderating factor in the relationship between formal management tools and actual process variability remains insufficiently explored.

The identified research gap provides the basis for proposing a model of relationships between quality management, organisational culture, process variability, and their reliability and efficiency, presented in the subsequent part of the article.

5. Results of the analysis

The conducted analysis of secondary data made it possible to identify patterns and differences in the approaches of the analysed companies to process management, quality, and operational stability. The results were organised according to the four analytical areas defined in the methodology.

The analysis was based on management reports and annual reports for 2024 from the analysed companies (KGHM Polska Miedź S.A., 2025; Grupa Kapitałowa Lubelski Węgiel Bogdanka S.A., 2025; ORLEN S.A., 2025; TAURON Polska Energia S.A., 2025), prepared in accordance with current non-financial reporting requirements, including CSRD and ESRS (EFRAG, 2023; The European Parliament & The Council of the European Union, 2022).

5.1. Approach to quality management and process improvement

In all the analysed companies, quality management has a systemic character and is closely integrated with operational and risk management; however, it rarely appears as a distinct, autonomous reporting area. Instead, quality-related elements are dispersed across business models, internal control systems, and management processes.

In the analysed companies, there is a clear dominance of an approach based on process formalisation and the standardisation of operational activities, which constitutes a fundamental mechanism for reducing variability. Management structures and the assignment of responsibility for process execution within segmental or functional frameworks play a particularly important role.

At the same time, there is a noticeable lack of direct references to classical quality management methods, such as Lean or Six Sigma. This indicates that quality in the analysed companies is embedded in the way they are managed – it is present in practice, although not always explicitly distinguished or clearly defined.

5.2. Method of identifying and reporting operational deviations

The analysed reports do not include direct measures of process deviations in a technological sense; however, they provide a wide range of information enabling their indirect identification. Operational deviations are primarily captured through:

- analysis of financial and operational performance in relation to previous periods;
- identification of factors influencing changes in production levels, costs, and revenues;
- reporting of extraordinary events and external factors;
- a systemic approach to risk management.

From this perspective, deviations are not presented as a process phenomenon sensu stricto, but rather as the result of the impact of operational and market variability on organisational performance. A key role is played by the managerial perspective, which focuses on interpreting the causes of changes and their impact on the achievement of business objectives.

In the analysed companies, a clear linkage is observed between performance reporting and risk management systems, indicating an increasing integration of operational and strategic perspectives in the identification of deviations.

5.3. Elements of organisational culture

The analysis of ESG reports and sections related to human resource management indicates that organisational culture plays a significant role in shaping process stability, although its impact is indirect.

In particular, the analysed companies strongly emphasise:

- occupational safety as a key organisational value;
- employee competence development and training;
- formal systems of responsibility and supervision;
- internal communication and employee engagement.

These elements point to the dominance of a formal-operational culture, in which procedures, standards, and compliance control play a central role. At the same time, references to a bottom-up culture of continuous improvement are limited, which may indicate a relatively low level of internalisation of quality practices at the operational level.

It is worth noting that organisational culture in the analysed cases is strongly linked to safety and regulatory compliance, which is characteristic of sectors with a high level of operational risk.

5.4. Indirect indicators of operational stability

The operational stability of the companies analysed was assessed based on indirect indicators available in the reports. In particular, the following were considered:

- repeatability of production and sales performance;
- level and structure of operating costs;
- ability to maintain business continuity under conditions of environmental variability;
- identified operational risks and the methods used to mitigate them.

In the classification process, fragments indicating repeatable performance, continuity of operations, developed control mechanisms, integration with risk management, and effective preventive actions were interpreted as signs of higher operational stability. In contrast, fragments referring to disruptions, strong dependence on geological, technological, regulatory, or market conditions, fluctuations in production or costs, or extraordinary operational events were interpreted as signs of greater exposure to variability.

For example, references to systematic risk monitoring, stable production capabilities, and continuity of key processes were classified as indicators of stability, whereas descriptions of production disturbances, cost pressure, or the influence of external and geological factors were classified as indicators of instability or increased sensitivity to variability. This classification logic was then used to synthesise the comparative interpretation presented in Tab. 2.

The results indicate that the analysed companies achieve a relatively high level of operational stability; however, it is largely dependent on external factors such as market conditions, regulatory frameworks, and geological and technological constraints.

At the same time, a strong relationship is observed between the degree of process formalisation and the organisation's ability to reduce variability. Companies with more developed management structures and control systems demonstrate a greater capacity to absorb disruptions and maintain stable performance.

5.5. Synthesis of research results

The analysis conducted indicates that in the analysed companies, there is a clear relationship between quality management, organisational culture, and operational stability; however, this relationship is largely indirect and not explicitly articulated in reporting.

The identified patterns suggest that:

- process quality is achieved through formalisation and control;
- deviations are analysed at the level of outcomes rather than directly at the process level;
- organisational culture supports stability primarily through safety and compliance;
- operational stability results from the integration of process and risk management.

A synthetic summary of the analysis results for the individual companies is presented in Tab. 2. In addition to the characterisation of the four analytical areas, the table also includes a synthetic dimension referred to as the 'level of integration', understood as the degree of coherence between quality management, organisational culture, and the mechanisms shaping operational stability. This allows for a comparative assessment of the analysed companies in terms of the level of integration across these areas.

Tab. 2. Synthetic overview of the comparative analysis results of the analysed companies

Area of analysis	KGHM Polska Miedź S.A.	TAURON Polska Energia S.A.	ORLEN S.A.	Lubelski Węgiel Bogdanka S.A.
Quality management and process improvement	systemic approach, strong process formalisation, integration with risk management	quality integrated with operational management and internal control, structural approach	quality embedded in the business model, strong integration with operational management	operational approach, process formalisation, less explicit systematisation of quality management
Reporting of operational deviations	developed reporting of influencing factors, strong link with risk and performance analysis	reporting based on analysis of results and financial deviations	broad analysis of factors influencing results, high level of managerial reporting	less developed reporting, greater emphasis on production factors
Organisational culture	strong emphasis on safety, formal responsibility structures, competence development	formal-operational culture, emphasis on compliance and responsibility	culture of compliance, responsibility, and operational efficiency	strong safety culture, limited references to bottom-up improvement
Operational stability	high, but dependent on geological and operational conditions	moderate, dependent on market and regulatory conditions	high, resulting from scale of operations and diversification	more variable, strongly dependent on operational conditions
Synthetic conclusion	stability achieved through formalisation and integration of quality management with risk	stability built through management structures and control systems	stability achieved through scale, process integration, and advanced reporting	greater sensitivity to variability with limited formalisation of quality management
Level of integration – comparative interpretation	high: coherent link between quality, risk, and stability	moderate: dominance of formal structures, partial integration	high: strong integration of processes, reporting, and management	varied: elements of formalisation present, but with limited systemic integration

Source: own elaboration based on annual reports of the analysed companies

The obtained results allow for a synthetic representation of the mechanism shaping operational stability, as presented in Fig. 3, which summarises the findings of the empirical analysis. This mechanism indicates that quality management – through process standardisation and control – serves as a mechanism for reducing operational variability, leading to increased process reliability and greater stability of outcomes.

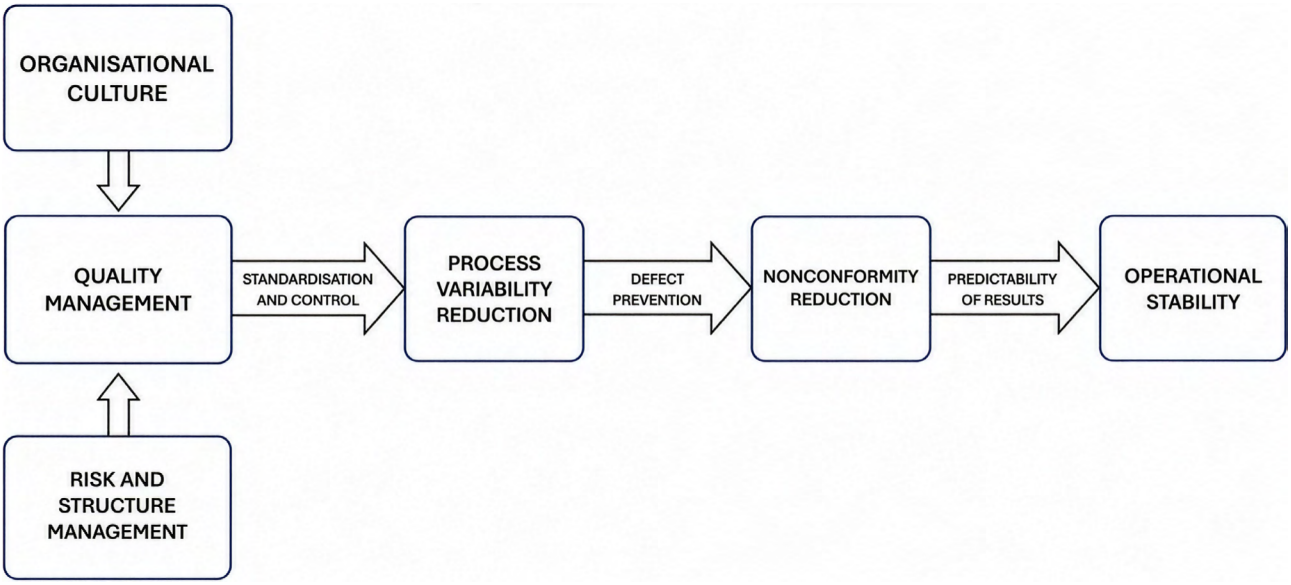

Fig. 3. Mechanism of shaping operational stability

At the same time, the effectiveness of this mechanism is determined by organisational culture, as well as by management structures and risk management practices, which can either strengthen or limit its impact.

Consequently, the operational stability of the analysed companies can be interpreted as a function of the level of integration between quality management, organisational culture, and management structures, which is directly reflected in the differentiated results presented in Tab. 2.

6. Relational model

Based on the conducted literature review and the analysis of annual reports, a relationship model is proposed in Fig. 4, representing a generalisation of the mechanism identified in the study (cf. Fig. 2). This model integrates three key dimensions of organisational functioning: organisational culture, quality management, and operational stability.

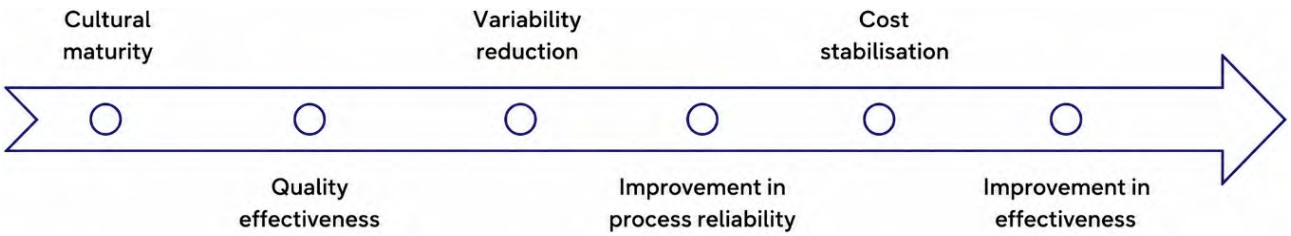

Fig. 4. Relational model

The model assumes that the maturity of organisational culture constitutes a key factor determining the effectiveness of quality management. A culture based on responsibility, safety, and openness to reporting deviations fosters the actual implementation of quality practices, extending beyond their purely formal character.

Within the model, quality management serves as a mechanism for reducing process variability through the standardisation of activities, control of operational

parameters, and systematic analysis of deviations. The reduction of variability leads to increased process reliability, understood as the ability to achieve consistent results under conditions of a variable operational environment.

Increased reliability translates into the stabilisation of unit costs and improved predictability of economic outcomes, which directly affects the quality of managerial decision-making and overall organisational efficiency.

An important component of the model is the role of management structures and risk management systems, which act as integrative elements linking the individual components of the mechanism. The level of their development determines the degree of alignment between quality management and operational outcomes, as well as the organisation's ability to absorb disruptions.

The model indicates that the key differentiating factor among the analysed companies is not the presence of individual system components, but the level of their mutual integration. A high level of integration leads to a coherent interaction of all components, reflected in stable operational outcomes. In contrast, a low or uneven level of integration limits the effectiveness of quality management and increases the susceptibility of processes to variability.

At the same time, the model should not be interpreted as a closed, strictly one-directional causal chain. Although the analytical logic adopted in the article emphasises the influence of organisational culture maturity on quality management effectiveness and process reliability, the relationships may also have a reciprocal character. Stable processes, reliable operational data, and effective quality management systems can reinforce organisational learning, increase trust in measurement systems, and support the further maturation of organisational culture.

The proposed model integrates insights from the bibliography, combining the quality perspective, the process approach, and the cultural dimension into a coherent interpretative framework tailored to the specificity of extraction processes (Davenport, 1993; Deming, 2018; Hammer & Champy, 2003; Juran, 1989; Schein & Schein, 2017).

Based on the conducted analysis, the model was further refined through the formulation of the following propositions:

- P1 (decoupling effect) – In organisations characterised by a high level of formalisation and a compliance-oriented culture, quality management practices become decoupled from actual process variability, limiting their effectiveness as a mechanism for its reduction.
- P2 (measurement level shift) – The identification of deviations primarily at the level of financial results or aggregated operational indicators, rather than at the process level, reduces the organisation's ability to diagnose and reduce process variability.
- P3 (data distortion mechanism) – A low level of organisational trust and limited openness to reporting deviations foster systematic distortions in operational data, thereby weakening the effectiveness of quality management systems.
- P4 (integration threshold) – The impact of quality management on process reliability is conditioned by the level of integration between organisational culture, management systems, and risk management structures.

7. Discussion

The conducted study and the proposed relationship model indicate that the reliability of extraction processes should not be interpreted solely as a technical category, but rather as the result of the integration of organisational, managerial, and

cultural mechanisms. In particular, the empirical findings confirm that operational stability is not a direct outcome of individual quality management tools, but rather the result of their embedding within a coherent organisational system.

The analysis of annual reports revealed significant differences among the analysed companies in the level of integration of quality management, organisational culture, and the mechanisms shaping operational stability. Entities characterised by a higher level of such integration demonstrate a greater ability to reduce variability and maintain stable performance, which is reflected both in their management structures and in their reporting practices. These findings are consistent with the literature indicating that the integration of technical, organisational, and cultural factors is a key condition for effective process management in highly variable environments (Arcidiacono et al., 2025; Elmarzouki & Jiuhe, 2026).

From the perspective of operational controlling, this implies that process quality directly translates into the quality of managerial information. Under conditions of high process variability, data used for budgeting, forecasting, and project evaluation are subject to greater uncertainty, thereby increasing decision-making risk. In contrast, process stabilisation leads to reduced variability in cash flows, improved predictability of outcomes, and enhanced reliability of managerial decisions. This perspective aligns with the classical view of management as a system for reducing variability and building organisational predictive capabilities (Deming, 2018).

The findings also indicate that, in the analysed companies, quality management is largely implicit; it is present in operational practice through process formalisation and control systems, yet rarely functions as a distinct, explicitly communicated system. At the same time, the observed approach is consistent with studies highlighting the importance of integrating practices such as TQM and TPM to improve stability and operational performance (Sahoo, 2019). This confirms that the effectiveness of quality management depends not only on the application of specific tools but also on their embedding within a broader organisational context (Aleu & Van Aken, 2016).

The analysis also highlights the role of organisational culture as a moderating factor in the effectiveness of quality mechanisms. In the analysed companies, a formal-operational culture predominates, strongly linked to safety and regulatory compliance, which is characteristic of sectors with high operational risk, such as mining. At the same time, the limited presence of bottom-up improvement practices may indicate untapped organisational potential for reducing process variability. These conclusions are consistent with the literature emphasising the importance of leadership, employee engagement, and openness to error reporting for the effectiveness of quality-related activities (Abushaikha et al., 2025).

The decoupling effect identified in the study may be explained by the dominance of formalisation and compliance-oriented management practices. In highly regulated and high-risk sectors, procedures and standards are necessary, but they may become primarily audit- or reporting-oriented if they are not internalised at the operational level. In such cases, quality management practices exist formally, while their actual impact on reducing process variability remains limited.

Several mechanisms may contribute to this effect, including incentive systems that reward formal compliance rather than identifying real process problems, hierarchical decision-making, high power distance, limited psychological safety, reluctance to report errors or deviations, and insufficient use of process-level data. This means that the effectiveness of quality management depends not only on the existence of procedures but also on whether the organisational culture supports trust, employee involvement, openness to deviations, and learning from operational problems.

In the context of ongoing digitalisation and the development of the Quality 4.0 concept, the relationship between process quality and data quality becomes

particularly important. The findings confirm that the effective use of analytical tools, including artificial intelligence and predictive models, requires stable processes and coherent reporting systems. Otherwise, such systems reproduce variability and uncertainty rather than reduce them. This is consistent both with the Quality 4.0 concept (Dias et al., 2022) and with studies highlighting the importance of integrating digital tools with quality management practices and organisational processes (Maheshwari & Devi, 2024; Yadav et al., 2021). Moreover, it is emphasised that the effective implementation of data-driven solutions requires an appropriate level of organisational maturity and the capability to use them in decision-making processes (Gardas & Narwane, 2024; Omar et al., 2019).

From a broader perspective, the findings have important implications for the transformation of the mining sector, where increasing pressure is placed on efficiency, transparency, and ESG reporting. The results indicate that the ability of companies to reduce operational uncertainty is linked to the level of integration of quality management, organisational culture, and managerial mechanisms. The integration of these elements enhances the quality of managerial information and supports the development of organisational predictive capabilities, which is consistent with the literature emphasising the importance of combining quality, organisational, and technological approaches in highly variable environments (Arcidiacono et al., 2025; Elmarzouki & Jiuhe, 2026). In this sense, operational stability can be considered a necessary condition for effective sectoral transformation, rather than merely its outcome.

The proposed model should also be considered in terms of possible reverse causality and feedback loops. While the study assumes that organisational culture maturity influences the effectiveness of quality management and process reliability, stable operational outcomes may in turn strengthen cultural maturity. Reliable data, repeatable processes, and visible effects of improvement activities can increase trust in management systems and reinforce behaviours oriented towards responsibility, learning, and continuous improvement. Therefore, the model is best understood as a dynamic relational mechanism rather than a simple linear sequence.

8. Conclusions

The conducted study indicates that the reliability of extraction processes is the result of the integration of quality management, organisational culture, and managerial mechanisms. Operational stability does not arise from the application of individual tools, but from their embedding within a coherent organisational system.

The findings confirm that quality management serves as a mechanism for reducing process variability; however, its effectiveness depends on the organisational context, particularly the maturity of organisational culture and the level of integration of management systems.

The study identified the presence of a decoupling effect, manifested as a discrepancy between formally declared quality practices and their actual impact on process execution. In particular, the identification of deviations is focused on the level of outcomes rather than processes, which limits the organisation's ability to reduce variability.

An important conclusion concerns the role of operational data quality, which determines both the effectiveness of quality management and the quality of managerial decision-making. Process stability constitutes a necessary condition for the effective use of analytical and predictive tools.

The key factor differentiating the analysed companies is the level of integration between quality management, organisational culture, and management structures. A higher level of integration translates into a greater ability to reduce variability and maintain operational stability.

In the context of the transformation of the mining sector, the findings highlight the need to combine technical and organisational perspectives. Stable processes, reliable data, and a mature organisational culture constitute the foundation of economic efficiency and a prerequisite for the effective implementation of digital solutions.

The study has several limitations. First, it is qualitative and exploratory in nature and is based on a purposive sample of four Polish companies operating in the raw materials, mining, and energy sectors. Therefore, the findings should not be interpreted as statistically representative of all companies or sectors. Second, the analysis relies on secondary data from annual and management reports, which means that the scope of interpretation is limited by the structure, level of detail, and communication objectives of these reports. Third, process variability was assessed indirectly, because the analysed reports do not provide detailed process-level reliability indicators such as downtime frequency, time between failures, or quantitative variability measures for individual operational processes.

These limitations affect the external validity. The proposed model may be analytically useful for other high-variability industrial sectors, such as heavy industry, manufacturing, logistics, or infrastructure-intensive activities, but its applicability should be verified through further empirical research in other countries, sectors, and firms of different sizes. Future studies should also include direct process-level data and longitudinal designs to examine reciprocal relationships between organisational culture, quality management, and process reliability.

From a practical perspective, the results indicate that enterprises operating in high-variability environments should treat quality management not only as a formal system of procedures but as a mechanism for reducing operational uncertainty. This requires stronger integration between quality management, risk management, operational reporting, and organisational culture. Particular attention should be paid to process-level measurement, the quality of operational data, the reporting of deviations, and the creation of organisational conditions that support openness, trust, and learning.

The findings are also relevant for the implementation of digital tools and Quality 4.0 solutions. Analytical and predictive systems can support decision-making only when they are based on stable processes, reliable data, and a mature organisational context. Therefore, the development of digital solutions should be accompanied by activities aimed at reducing process variability and strengthening a culture of continuous improvement.

References

Abushaikha, I., Bwaliez, O. M., Yaseen, M., Hamadneh, S., & Darwish, T. K. (2025). Leveraging animal feed supply chain capabilities through big data analytics: A qualitative study. *International Journal of Quality & Reliability Management*, *42*(9), 2605–2625. https://doi.org/10.1108/IJQRM-01-2024-0012

Aleu, F. G., & Van Aken, E. M. (2016). Systematic literature review of critical success factors for continuous improvement projects. *International Journal of Lean Six Sigma*, *7*(3), 214–232. https://doi.org/10.1108/IJLSS-06-2015-0025

Antony, J., Snee, R., & Hoerl, R. (2017). Lean Six Sigma: Yesterday, today and tomorrow. *International Journal of Quality & Reliability Management*, *34*(7), 1073–1093. https://doi.org/10.1108/IJQRM-03-2016-0035

Arcidiacono, G., Antonacci, A., & Antony, J. (2025). The r-evolution of Lean Six Sigma from Industry 4.0 to Society 5.0: Excellence 5.0. *International Journal of Quality & Reliability Management*, *42*(8), 2328–2349. https://doi.org/10.1108/IJQRM-11-2024-0415

Davenport, T. H. (1993). *Process Innovation: Reengineering Work Through Information Technology*. Harvard Business School Press.

Deming, W. E. (2018). *Out of the Crisis*. MIT Press.

Dias, A. M., Carvalho, A. M., & Sampaio, P. (2022). Quality 4.0: Literature review analysis, definition and impacts of the digital transformation process on quality. *International Journal of Quality & Reliability Management*, *39*(6), 1312–1335. https://doi.org/10.1108/IJQRM-07-2021-0247

EFRAG. (2023). *European Sustainability Reporting Standards (ESRS)*. European Financial Reporting Advisory Group. https://xbrl.efrag.org/e-esrs/esrs-set1-2023.html

Elmarzouki, M., & Jiuhe, W. (2026). Hybrid innovation models for productivity growth: The role of Lean, Six Sigma and Industry 4.0 integration. *International Journal of Lean Six Sigma*, *17*(1), 71–117. https://doi.org/10.1108/IJLSS-01-2025-0003

Gardas, R., & Narwane, S. (2024). An analysis of critical factors for adopting machine learning in manufacturing supply chains. *Decision Analytics Journal*, *10*, Article 100377. https://doi.org/10.1016/j.dajour.2023.100377

Hammer, M., & Champy, J. (2003). *Reengineering the Corporation: A Manifesto for Business Revolution*. HarperCollins.

Johnson, K., Morais, C., & Patelli, E. (2025). Enhancing procedure quality: Advanced language tools for identifying ambiguity and high-potential violation triggers. *Reliability Engineering & System Safety*, *264*(A), Article 111308. https://doi.org/10.1016/j.ress.2025.111308

Juran, J. M. (1989). *Juran on Leadership for Quality: An Executive Handbook*. Free Press, Collier Macmillan.

KGHM Polska Miedź S.A. (2025). *Sprawozdanie Zarządu z działalności KGHM Polska Miedź S.A. oraz Grupy Kapitałowej KGHM Polska Miedź S.A. w 2024 roku*. https://s.agh.edu.pl/cax6v

Grupa Kapitałowa Lubelski Węgiel Bogdanka. (2025). *Sprawozdanie Zarządu z działalności LW Bogdanka S.A. oraz Grupy Kapitałowej LW Bogdanka za 2024 r.* https://s.agh.edu.pl/FA1qM

Maheshwari, P., & Devi, Y. (2024). Investigating the relationship between Lean Six Sigma performance strategy with digital twin modeling: Practices and factors. *Journal of Cleaner Production*, *436*, Article 140449. https://doi.org/10.1016/j.jclepro.2023.140449

Narayanamurthy, G., & Gurumurthy, A. (2016). Leanness assessment: A literature review. *International Journal of Operations & Production Management*, *36*(10), 1115–1160. https://doi.org/10.1108/IJOPM-01-2015-0003

Omar, Y. M., Minoufekr, M., & Plapper, P. (2019). Business analytics in manufacturing: Current trends, challenges and pathway to market leadership. *Operations Research Perspectives*, *6*, Article 100127. https://doi.org/10.1016/j.orp.2019.100127

ORLEN S.A. (2025). *Sprawozdanie Zarządu z działalności Grupy ORLEN i ORLEN S.A. za 2024 rok*. ORLEN S.A. https://s.agh.edu.pl/gQD53

Orošnjak, M., Brkljač, N., & Ristić, K. (2025). Fostering cleaner production through the adoption of sustainable maintenance: An umbrella review with a questionnaire-based survey analysis. *Cleaner Production Letters*, *8*, Article 100095. https://doi.org/10.1016/j.clpl.2025.100095

Patel, A. S., & Patel, K. M. (2021). Critical review of literature on Lean Six Sigma methodology. *International Journal of Lean Six Sigma*, *12*(3), 627–674. https://doi.org/10.1108/IJLSS-04-2020-0043

Pierli, G., Murmura, F., & Bravi, L. (2026). Lean manufacturing and sustainability pillars: A systematic literature review. *International Journal of Lean Six Sigma*, *17*(8), 1–26. https://doi.org/10.1108/IJLSS-09-2024-0197

Sahoo, S. (2019). Assessment of TPM and TQM practices on business performance: A multi-sector analysis. *Journal of Quality in Maintenance Engineering*, *25*(3), 412–434. https://doi.org/10.1108/JQME-06-2018-0048

Schein, E. H., & Schein, P. (2017). *Organizational Culture and Leadership* (5th ed.). Wiley.

Seth, D., Shrivastava, R. L., & Shrivastava, S. (2016). An empirical investigation of critical success factors and performance measures for green manufacturing in cement industry. *Journal of Manufacturing Technology Management*, *27*(8), 1076–1101. https://doi.org/10.1108/JMTM-04-2016-0049

TAURON Polska Energia S.A. (2025). *Sprawozdanie Zarządu z działalności TAURON Polska Energia S.A. oraz Grupy Kapitałowej TAURON za rok obrotowy 2024*. TAURON Polska Energia S.A. https://s.agh.edu.pl/uLWs5

The European Parliament & The Council of the European Union (2022). Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting. *Official Journal of the European Union*, L 322/15, https://eur-lex.europa.eu/eli/dir/2022/2464/oj?eliuri=eli%3Adir%3A2022%3A2464%3Aoj&locale=en

Yadav, N., Shankar, R., & Singh, S. P. (2021). Critical success factors for lean six sigma in quality 4.0. *International Journal of Quality and Service Sciences*, *13*(1), 123–156. https://doi.org/10.1108/IJQSS-06-2020-0099