

YEAR/ROČNÍK 30
1/2026

ISSN 1338-984X (on-line)
EV 3722/09

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LUDMILA JIŘÍČKOVÁ, PETR DOUCEK

Quality Management: Application of the DMAIC Tool to Prevent Paint Rework on Excavator Buckets

DOI: 10.12776/qip.v30i1.2279

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Received: 27-10-2025 Accepted: 02-03-2026 Published: 30-04-2026

ABSTRACT

Purpose: This work aims to apply the DMAIC methodology to solve a problem of paint rework on buckets during the storage process at a heavy machinery company in the South of Rio de Janeiro.

Methodology/Approach: The technical procedures adopted for the research are based on the case study approach. This methodological classification allows for an in-depth and detailed investigation of a singular case.

Findings: With this solution, we were able to reduce rework and consequently cut the costs of re-painting parts, which can also be highlighted as the main applied contribution of this work, since these results can support other companies that will go through the same process.

Research Limitation/Implication: It is important to note that there was not enough time to collect results after implementing the device. For future research, it is suggested that the company continue to invest in continuous improvement processes, using methodologies with different approaches.

Originality/Value of paper: The need to avoid painting rework, due to the associated costs, highlights the importance of the structured approach proposed. Data analysis showed that more than 40% of the buckets produced by the company had paint scratches, generating 63 hours of rework and a cost of R\$ 124,988.51.

Category: Research paper

Keywords: quality management; Lean Six Sigma; DMAIC; continuous improvement; zero defects

Research Areas: Quality Management

1 INTRODUCTION

Quality management plays a fundamental role in the quest for operational excellence and meeting customer expectations. In the industrial context, the occurrence of problems that lead to rework can result in delays, waste, and significant losses. It is therefore crucial to use effective methodologies to identify, analyse and solve these problems in order to minimise their impact and guarantee the continuity of the production process (Godina, Silva, & Espadinha-Cruz, 2021; Enache et al., 2023; Tsung & Wang, 2023). Quality management plays a fundamental role in ensuring that an organisation achieves high standards of excellence in its products or services. First and foremost, it aims to satisfy customers' needs and expectations. Through the implementation of practices and processes aimed at continuous improvement, quality management allows the company to identify and correct possible faults, offering reliable, durable products that meet the established specifications and requirements (Santos & Millán, 2013; Azevedo et al., 2019; Vieira et al., 2019; Silva et al., 2020; Chero Yenque et al., 2022; Talapatra, Santos, & Gaine, 2022; Makinde et al., 2022; Craveiro et al., 2023), to promote innovation (Santos et al., 2019; Zgodavova et al., 2020; Murmura, Bravi, & Santos, 2021; Yülek & Santos, 2022; Santos et al., 2023), towards sustainability (Santos et al., 2014; Rebelo et al., 2016; Rodrigues et al., 2020; Teixeira et al., 2022; Sun et al., 2023).

One tool that can be used for this purpose is Define, Measure, Analyse, Improve, Control (DMAIC), which is part of the Six Sigma methodology. DMAIC is a structured and systematic approach that seeks to improve existing processes by identifying opportunities for improvement, analysing root causes, implementing solutions and establishing controls to maintain the results achieved (Knop, 2022; Ramos & Rodríguez, 2022; Tsung & Wang, 2023). Once DMAIC has been defined as the tool to be applied to the problem, a project team will create a project charter to be followed during the process. It should contain all five phases of the cycle, which can be used with different tools because it is a flexible cycle, which will be fundamental to helping the improvement process (Knop, 2022; Ramos & Rodríguez, 2022; Tsung & Wang, 2023).

In a company, it is essential to eliminate problems that generate unnecessary costs. In this way, rework must be avoided, reducing the costs of materials and labour. Therefore, applying DMAIC as a solution to this problem becomes a relevant and promising strategy for improving efficiency and quality in an organisation's processes. By applying DMAIC, the company can obtain a structured, data-based approach to identifying the root cause and implementing effective solutions (Knop, 2022; Ramos & Rodríguez, 2022; Tsung & Wang, 2023). Thus, the research question that can guide the development of this work is: What impact does the application of the Six Sigma methodology using the DMAIC tool have on improving industrial processes in terms of operational efficiency, product quality and cost reduction? Therefore, the aim of this research is to explore the application of DMAIC as a quality management tool to prevent rework on bucket painting on

excavator machines. The main concepts and stages of DMAIC will be covered, as well as its theoretical and practical framework in quality management. In addition, a case study will be carried out in an industrial company in the heavy machinery sector, with the aim of identifying the challenges and benefits of applying DMAIC in this specific context.

2 THEORETICAL REFERENTIAL

This section reviews the scientific literature with the aim of presenting the theoretical foundations of the central themes of this research: Quality Management, DMAIC and Lean Six Sigma (LSS). The approach adopted aims to provide an in-depth understanding of these concepts, highlighting their importance in process optimisation and the search for organisational efficiency.

Quality management is a set of practices and processes designed to guarantee excellence and customer satisfaction in relation to the products and services provided by an organisation. It involves planning, implementing and controlling quality-related activities with the aim of continuous improvement (Jirasukprasert et al., 2014; Ismail et al., 2023; Hamdan et al., 2024). A fundamental aspect of quality management is to define clear standards and specifications for products or services to ensure that they meet customer needs and expectations. The aim of quality management is to guarantee excellence, efficiency and consistency in all areas of the company, with a view to continuous improvement (Castro et al., 2020; Khalilinezhad et al., 2021; Solanki & Desai, 2021; Kumar et al., 2023; Escobar et al., 2023).

In addition, quality management involves the adoption of preventive and corrective measures to avoid problems and failures in products or services. This includes identifying and analysing risks, implementing controls and carrying out internal audits to check compliance with established standards (Mandal, 2012; Chen et al., 2023; Hannafin et al., 2023). Quality management also promotes the use of tools and techniques such as process mapping, root cause analysis and performance indicator management, which make it possible to monitor and evaluate the effectiveness of the actions implemented (Amitrano et al., 2016; Knop, 2022; Bai et al., 2023).

The DMAIC methodology, in which each letter is used in a phase, was used as a case study in this research to solve excessive painting rework on excavator buckets. This cycle is one of the Six Sigma tools. DMAIC is a continuous improvement approach, and its implementation in the organisation aims to reduce costs and waste. It solves problems related to failures, excessive costs and time, thus improving the quality of processes (Knop, 2022; Ramos & Rodríguez, 2022; Prado et al., 2023). Lean Six Sigma uses a set of Lean tools to increase productivity. While Six Sigma aims to reduce damage. DMAIC will help achieve these objectives. This methodology is used to improve quality and reduce problems in existing processes, where the cause of the problem is not well specified. This

method points out the importance of analysing data before starting to solve problems and apply improvements. Through the five stages, this quality approach is applied (Enache et al., 2023; Pongboonchai-empl et al., 2023; Uluskan & Karşı, 2023).

DMAIC is contained in the Six Sigma methodology, which provides significant benefits for organisations, as it seeks to analyse process performance, aiming to increase performance, reduce costs, improve cycle time by reducing non-value-added steps and avoiding waste. In addition to improving the quality of the product or service and reducing errors that may appear in the process, this will generate customer satisfaction and improve employee morale. (Alshamlan et al., 2022; Pongboonchai-empl et al., 2023; Tsung & Wang, 2023). Continuous progression leads to better quality products and services, meeting customer expectations and increasing customer satisfaction. At the same time, when employees see the positive results of the improvements implemented, their motivation and engagement are strengthened (Uluskan, 2016; Adeodu et al., 2023; Uluskan & Karşı, 2023).

Applying DMAIC helps to solve problems, due to the organisation of the steps, techniques and tools that help to acquire diagnoses and generate and analyse decision alternatives. These tools help to collect and analyse data, diagnose problems and generate decision alternatives for improving processes (Escobar et al., 2022; Bonetti et al., 2023; Condé et al., 2023). DMAIC serves to develop or improve a process, reaching a high level of process capability and working on identifying and almost eliminating the main causes responsible for customer dissatisfaction, allowing the project team to develop effective solutions based on facts and data, rather than making decisions based on assumptions or subjective experience (Solanki & Desai, 2021; Gomes et al., 2022).

Toyota in Japan developed the Toyota Production System in the 1940s. This approach is understood as a management system that integrates specific techniques aimed at eliminating waste in both internal and external processes. Its purpose is to eliminate waste in production and improve efficiency, playing an essential role in improving an organisation's production and competitiveness. Its foundations are based on stability and standardisation. Companies that have adopted Lean Manufacturing have seen positive impacts on their commercial performance, as well as their financial and environmental performance (Tsarouhas, 2021; Achibat et al., 2023; Neeru et al., 2023). This approach encompasses various management techniques that complement each other and are coherent, such as Just-in-Time (JIT), Total Quality Management (TQM), Total Productive Maintenance (TPM) and Human Resource Management (HRM). In addition to the direct benefits, the implementation of Lean Manufacturing also brings indirect benefits to organisations, such as improved quality and safety, reduced tracking time, a positive change in corporate culture, as well as reduced fatigue and stress. There are various Lean Manufacturing techniques and methods used by companies, such as Seiri, Seiton, Seiso, Seiketsu, Shitsuke (5S), Single Minute Exchange of Die

(SMED), Kanban, Kaizen, Poka-Yoke and other relevant tools. (Hollingshed, 2022; Mittal et al., 2023; Tsarouhas & Sidiropoulou, 2023).

3 SCIENTIFIC METHOD

This section provides information on the research method adopted in this study. Initially, the classification of the research will be discussed, encompassing its nature, approach, objectives, and work procedures. Next, the stages of execution will be detailed, outlining the planning, data collection and analysis of the results. Next, the instruments used for data collection will be mentioned, highlighting their relevance in obtaining information. In addition, the methodological flow will be presented, describing the stages for the development of the research.

Scientific research encompasses various classifications related to its nature, approach, objectives and procedures (Kothari & Garg, 2019). In the context of this study, the classifications are highlighted in Table 1. This study was conducted by means of applied research, whose objectives were exploratory and descriptive, with a qualitative approach based on a case study. In this section, the definitions and particularities of these elements are presented, justifying the methodological choice adopted.

Table 1 – Research classification (Adapted from Cronin & George, 2023; Kothari & Garg, 2019; Reis et al., 2021)

Nature	Objective	Approach	Research procedures
Basic	Exploratory	Quantitative	Experiment
Applied	Descriptive	Qualitative	Survey
	Explanatory	Combined	Modelling
			Content analysis
			Case study

The research method adopted in this study is of an applied nature, given that its propositions seek applicability in a specific reality. As for the research objectives, they will be outlined in an exploratory and descriptive manner, allowing us to delve deeper into the elements of the investigation and, at the same time, observe, analyse, classify, and interpret the data impartially, without direct interference from the researcher. This methodological approach aims to ensure an understanding of the phenomena being studied, thus enabling an informed analysis (Miguel, 2018; Kothari & Garg, 2019).

The research adopted in this study is classified as qualitative, in which the aim is to understand and interpret the phenomenon under study through in-depth analysis of descriptive data. In this approach, the researcher plays a fundamental role as the main vehicle for conducting the research. Their role includes collecting information, analysing the data and interpreting the results in a contextualised way (Yin, 2017; Kothari & Garg, 2019).

The technical procedures adopted for the research are based on the case study approach. This methodological classification allows for an in-depth and detailed investigation of a singular case, with the aim of understanding, describing and analysing the phenomenon in its real context, aiming for the specificity of the case studied (Yin, 2017; Kothari & Garg, 2019). In this work, a case study was carried out in the heavy machinery sector.

This work was developed based on a problem encountered at a heavy machinery company in the southern region of Rio de Janeiro. The company specialises in the manufacture of heavy machinery, also known as the yellow line, as well as industrial vehicles such as forklift trucks. Its aim is to become a national industry that is fully integrated and adapted to the Brazilian market, offering excellence in service, sales, and technical assistance. The bucket is a fundamental part of excavator machines, playing an important role in their operations. It is designed to withstand the adverse conditions and challenges encountered in excavation environments. It is the part of the excavator that will dig, lift, and transport materials, as marked on Figure 1.

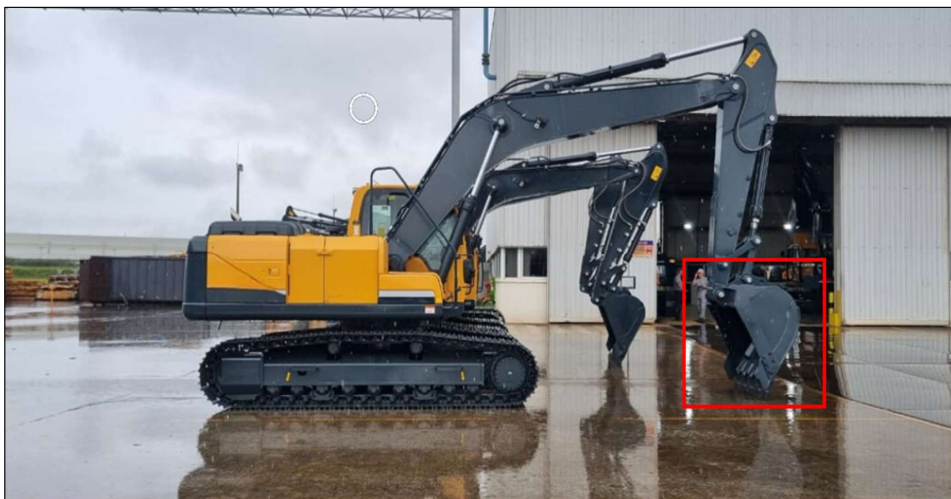


Figure 1 – Backhoe loader bucket

Its shape and size vary according to the specific application. This versatility makes the bucket a central part of the functionality of excavating machines, playing a crucial role in carrying out a wide range of construction and excavation tasks. The following is a flowchart as shown in Figure 2.

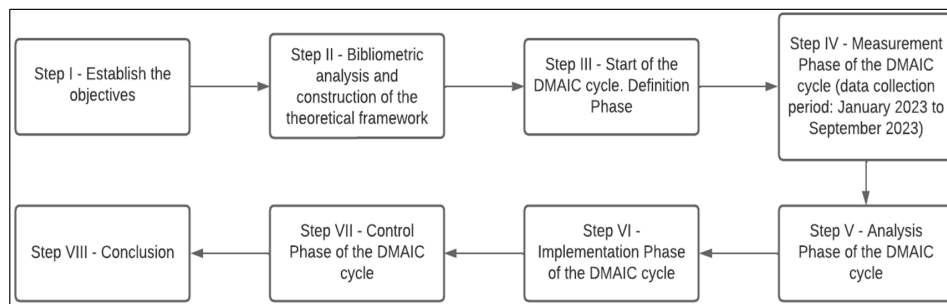


Figure 2 – Methodological flow

This study was divided into eight stages: Stage I – establishing the objectives; Stage II – bibliometric analysis and construction of the theoretical framework; Stage III – beginning of the DMAIC cycle. Definition phase; Stage IV – measurement phase of the DMAIC cycle; Stage V – analysis phase of the DMAIC cycle; Stage VI – improvement phase of the DMAIC cycle; Stage VII – control phase of the DMAIC cycle; Stage VIII – conclusion.

In stage I, the objectives of this work were defined, providing a purpose and direction to be followed. In stage II, Scopus searches were carried out to find articles on quality management and DMAIC. In this way, through bibliometric analysis, it was possible to build a theoretical framework based on published works with a good foundation. Moving on to stage III, the case study began. Using the DMAIC cycle, the definition phase began, with the aim of identifying opportunities for improvement and the project’s expectations.

Stage IV was the measurement phase, where it was possible to collect data to measure the performance of the process. Then, in stage V, the analysis phase, it was possible to understand the problem based on the data causing this undesired effect. In stage VI, the improvement phase, it was possible to identify solutions to eliminate the problem. Proceeding to stage VII, the control phase, it is possible to look for opportunities for continuous improvement by monitoring the process. Finally, stage VIII discusses the achievement of the objectives proposed in this study and their main contributions.

4 RESULTS AND DISCUSSIONS

To ensure methodological clarity, the management tools used in each DMAIC phase were explicitly defined. In the Define phase, the Project Charter, Ishikawa Diagram, and GUT matrix structured problem identification and prioritisation. In the Measure phase, performance data were collected to calculate rework rates and associated costs, supported by KPIs. Additionally, a SWOT matrix was conducted at this stage to consolidate validated quantitative findings into a structured strategic diagnosis. In the Analyse phase, data interpretation identified pallet contact as the root cause of paint damage. The Improve phase applied a 5W2H action plan,

leading to the implementation of a protective device. Finally, the Control phase established a formal Control Plan to sustain improvements through defined monitoring and corrective procedures. Initial analysis of the situation revealed that the collision between the heavy machinery bucket and the storage pallets was causing significant scratches. This resulted in substantial rework, where parts had to be repaired or repainted, increasing production costs and extending the time needed to complete each unit.

Through data collection, direct observations, and analysis of defective parts, it was possible to quantify the increase in paint consumption resulting from touch-ups and repainting. In addition, inspection of the affected parts demonstrated the recurring nature of the problem and its impact on product quality. To solve the problem, a protective device was created to prevent direct contact between the painted parts and the wooden pallets.

The continuous search for improvement has become a fundamental objective for companies. In this context, quality management plays a crucial role, providing a structured way to identify and resolve issues related to defects and failures and, at the same time, drive continuous improvement. DMAIC, a widely used analysis method in this context, offers a systematic approach to problem solving (Knop, 2022; Ramos & Rodríguez, 2022; Tsung & Wang, 2023). In the first stage, an Ishikawa Diagram was drawn up so that the possible causes of the problem could be identified more quickly and clearly (Figure 3).

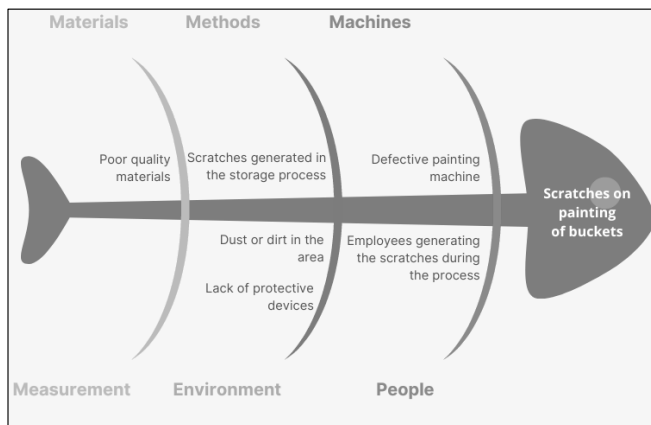


Figure 3 – Ishikawa diagram

In the second stage, a project charter was drawn up, as shown in Figure 4, in which the main definitions of the project were stated. In this way, it is possible to understand more clearly the objectives to be achieved, generating greater alignment between those involved.

<p>Business Case</p> <p>Machine buckets often come into contact with wooden pallets during the storage process, resulting in unwanted scratches.</p>	<p>Opportunity Definition</p> <p>Develop a definitive solution to eliminate unwanted scratches.</p>
<p>Goal Setting</p> <p>Implement improvements to eliminate contact between the bucket and wooden pallets, reducing rework and excessive paint consumption.</p>	<p>Project Scope</p> <p>-Reduce paint failures; -Reduce rework costs; -Improvement of the zero defects indicator.</p>
<p>Team</p> <p>-Manufacturing team; - Maintenance team; - Parts painting team.</p>	

Figure 4 – Project charter

In the third stage, the problems were defined, and their understanding made clearer. The GUT matrix was used as a prioritisation tool, assessing severity, urgency, and trend, according to Table 2.

Table 2 – The GUT matrix used

GUT Matrix					
#	Problem	Gravity	Urgency	Trend	Score
1	Devices/racks/pallets do not have protection	5	5	5	125
2	Need to create more devices to support the frames	4	4	3	48
3	Rework cost impact	5	5	5	125
4	Part of the team is being moved to carry out rework	3	3	3	27
5	Bad indicators	3	3	3	27

At the bucket storage stage, the wooden pallets result in scratches in the paintwork, which generates significant rework, as repainting must be carried out, causing an increase in paint consumption, directly affecting the efficiency and costs of the production process. To address this problem, a multidisciplinary team will be formed, made up of members from the quality, production, logistics, painting, and maintenance areas.

This team will analyse, propose, and implement solutions that minimise unwanted contact between the wooden pallets and the buckets during the storage process, reducing costs and rework, with a view to continuous improvement. In the last stage, a 5W2H was structured to define the tasks to be carried out and follow them up in a more practical and visual way (Table 3).

Table 3 – The 5W2H used

WHAT?	ACTION PLAN				PROJECT	Scratches on heavy machinery buckets
	WHY?	WHERE?	WHEN?	WHO?	HOW?	HOW LONG?
A protective device is required to assist with storage	- It is necessary to solve the problem of damage to painted parts during storage - Improvement in KPI	Location where buckets are stored	Immediately	Logistics, painting, quality, manufacturing, and maintenance	A device will be developed that has a resistant metal surface to suspend the buckets between drillings.	Estimated period: 1 month

The measurement phase acts as a fundamental pillar for the successful implementation of improvements and analysis in organisational processes. At this stage, data was collected using Microsoft Excel, so that a basis could be established for subsequent evaluations and improvements, as well as understanding the extent of the impact of problems. In this context, Table 5 presents data on rework on excavator model RB220C-9 buckets associated with painting problems, including the associated costs and the hours dedicated to these tasks, helping to identify opportunities for improvement and highlighting the relevance of this information to the success of process optimisation and cost reduction initiatives.

The data in Table 5 were collected over nine months, from January to September 2023. The number of machines reworked was determined using a production plan, according to Table 4, where each month contains several machines to be produced, and along with this, the percentage of defect history is multiplied to obtain the number of machines to be reworked. To calculate the total rework time, the chrono analysis method was used.

Table 4 – Production plan

Month	Quantity of machines	Failure history
January	109	42%
February	119	45%
March	105	48%
April	101	45%
May	115	41%
June	118	49%
July	104	47%
August	106	46%
September	110	44%

The average of five rework times resulted in 8.5 minutes, multiplied by the number of machines reworked. When calculating the cost of labour, the value of the factory

painter’s labour was taken as R\$5.08. This value was multiplied by the total rework time and the amount of labour. Retouching is done with a brush, which implies moderate paint consumption. The amount of paint used was calculated based on the average monthly consumption, which is 0.45L of paint to touch up one machine. The cost associated with this amount of paint is R\$12.22 per litre, and the total cost of the paint was obtained by multiplying these values. Finally, the total cost of the rework is the cost of the labour multiplied by the cost of the paint used.

Table 5 – Buckets rework

Issue data			Rework						
Month 2023	Class	Origin	Total	Labour	Total Rework Time (h)	Labour Cost	Quantity of Paint Used (L)	Cost of Paint Used	Total Cost in R\$
						5,08		12,22	
Jan	Damaged Paint	Intern	46	1	6.5	32.9	21	251.74	8,295.56
Feb	Damaged Paint	Intern	54	1	7.6	38.5	24	294.47	11,350.45
Mar	Damaged Paint	Intern	50	1	7.1	36.3	23	277.15	10,054.38
Apr	Damaged Paint	Intern	45	1	6.4	32.7	20	249.93	8,176.39
May	Damaged Paint	Intern	47	2	6.7	67.9	21	259.28	17,598.98
Jun	Damaged Paint	Intern	58	2	8.2	83.2	26	317.95	13,232.75
Jul	Damaged Paint	Intern	49	2	6.9	70.4	22	268.79	18,914.13
Aug	Damaged Paint	Intern	49	2	6.9	70.2	22	268.13	18,821.38
Sep	Damaged Paint	Intern	48	2	6.9	69.7	22	266.15	18,544.49

Aiming for a clearer understanding and more precise analysis of organisational operations, Key Performance Indicators (KPIs) were implemented, as shown in Figure 5. With the purpose of simplifying complexities and offering a comprehensive view of process performance, KPIs are tools that allow for an objective and quantitative assessment of progress towards established objectives. These indicators provide a framework for working with previously collected data, offering insights that direct actions towards specific areas that require attention and improvement.



Figure 5 – Analysis of KPIs

Although the Strengths, Weaknesses, Opportunities, and Threats (SWOT) matrix is traditionally positioned within the Define phase of the DMAIC framework, this study deliberately applied it during the Measure phase to consolidate empirically validated findings into a structured strategic diagnosis. Rather than serving as an exploratory instrument, the SWOT analysis was grounded in statistically validated performance indicators, ensuring alignment between quantitative evidence and strategic interpretation. The data collected in Measure revealed consistent patterns in rework rates, operational costs, and process variability, establishing a robust empirical foundation for integrating internal organisational factors, such as process capabilities and structural constraints. Based on this diagnostic consolidation, the project seeks to significantly reduce rework rates and optimise the costs associated with corrective activities. By mitigating rework and its financial impacts, the organisation aims to enhance operational efficiency, improve resource allocation, and reinforce sustainable corporate growth. Within this methodological design, the SWOT matrix (Figure 6) functioned as a strategic synthesis mechanism, supporting the prioritisation of critical variables and guiding targeted improvement initiatives in the subsequent stages of the DMAIC cycle.

As far as strengths are concerned, because the team involved in solving the problem is multidisciplinary, it can result in members with diverse skills, which can bring different perspectives to the solution, making it a strength. There is also the fact that the painting team has experienced collaborators. On the other hand, weaknesses include inadequate storage of the buckets and insufficient quality control during the storage and painting process. As for opportunities, there is the possibility of developing appropriate storage procedures and providing additional training for the painting team. Finally, the threats include the increase in rework costs and the negative impact on customer satisfaction, as by increasing the costs of the process, the value of the product increases.

SWOT ANALYSIS	
<p>STRENGTHS</p> <ul style="list-style-type: none"> • Multidisciplinary team; • Experience of the painting team. 	<p>WEAKNESSES</p> <ul style="list-style-type: none"> • Incorrect storage of buckets; • Insufficient quality control during the storage and painting process.
<p>OPPORTUNITIES</p> <ul style="list-style-type: none"> • Development of appropriate storage procedures; • Additional training for the painting team. 	<p>THREATS</p> <ul style="list-style-type: none"> • Increased rework costs; • Negative impact on customer satisfaction.

Figure 6 – The SWOT matrix used

This SWOT Analysis provides a comprehensive view of the internal and external variables that can influence success in reducing rework and its associated costs. By understanding the strengths and opportunities, while addressing the weaknesses and threats, the organisation can develop more effective strategies to achieve its goals. Previously, a challenge was identified related to the quality of paint on the parts of a heavy machinery company.



Figure 7 – Stored buckets

The buckets were showing paint problems during the storage and handling process, as shown in Figure 7. To solve the problem, we implemented a protective device designed to prevent direct contact between the painted parts and the storage pallets. This consists of a metal surface designed to support and protect the buckets. Its structure can support the weight of the buckets and suspend them between the holes in the bucket, preventing direct contact with the part that could cause scratches or damage to the paintwork.

After analysing the two-dimensional (2D) drawing of the bucket in Figure 8, here is the three-dimensional (3D) representation of the device using the SketchUp application, as shown in Figure 9. Using this tool made it possible to create a detailed and accurate virtual model. This will allow for a clearer and more in-depth visualization of the project, aiding in the design process, manufacturing, and communication with stakeholders, making it an important tool for product development.

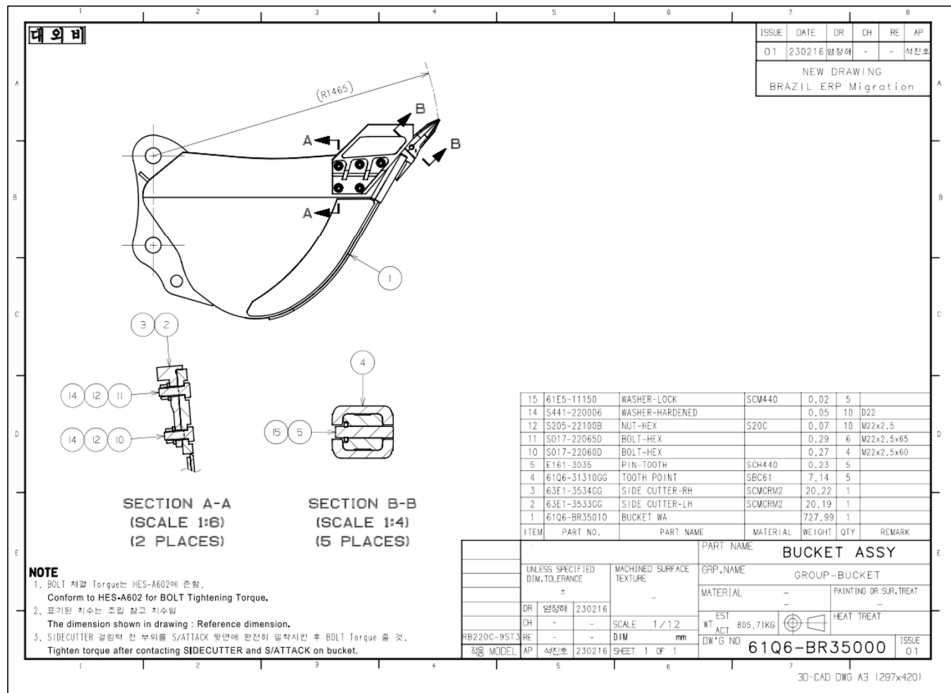


Figure 8 – Bucket 2D drawing

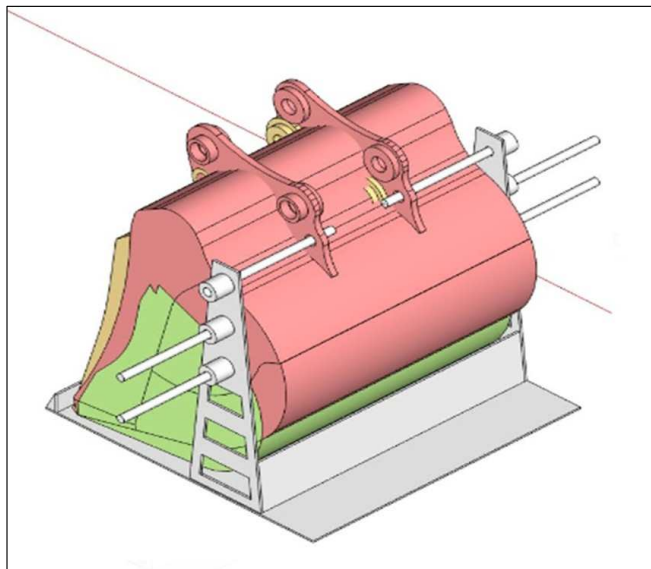


Figure 9 – Implemented device

In the Control phase, it is essential to ensure that the improvements implemented are maintained over time and that any deviations from the new process are promptly identified and corrected. To ensure this, a control plan was drawn up, as shown in Table 6, aimed at monitoring and maintaining the quality of the buckets and the efficient functioning of the support and protection system, whereby any scratched bucket must be immediately reported to the quality team.

Table 6 – Control plan

#	Measurements	Performance Standard	Description	Frequency	Responsible	Contingency pan	Where to Report?
	Indicator	Control and Specification Limits	What to check?	When to check?	Who will check?	Corrective action	
1	Number of buckets scratched	Every scratched bucket must be reported, regardless of quantity	If scratching occurred after storage	2 times per week	Quality team	- Bring together the team that participated in the project to analyse - Rework the paint	Quality team

5 CONCLUSION

This research set out to develop a solution to the problem encountered in a heavy machinery company using the DMAIC methodology. The analysis revealed that the collision between the wooden pallets and the buckets caused them to be

scratched during the storage process. The data collected showed that the company had a high cost of rework. In each month analysed, more than 40% of the buckets had to go through the painting rework process, which generated 63 hours of rework and a cost of R\$ 124,988.51.

By studying the problem using DMAIC and the quality tools, it was possible to develop a device that will protect the buckets of the excavators, preventing any kind of collision during storage, so as not to scratch the paintwork. With this solution, the company was able to reduce rework and consequently cut the costs of re-painting parts, which can also be highlighted as the main applied contribution of this work, since these results can support other companies that will go through the same process. It is important to note that there was not enough time to collect results after implementing the device. For future research, it is suggested that the company continue to invest in continuous improvement processes, using methodologies with different approaches. Furthermore, expanding the scope to identify and resolve other improvement points within the production chain could provide additional benefits.

ACKNOWLEDGEMENTS

This study was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior — Brazil (CAPES) — Financial Code 001 and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), with the collaboration of Gilberto Santos who acknowledge Fundação para a Ciência e a Tecnologia (FCT) for its financial support to LAETA via project-UID/50022/2025 (DOI: <https://doi.org/10.54499/UID/50022/2025>).

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Conceptualization, G.C.C., L.A.S. and J.S.M.R.; Methodology, G.C.C. and L.A.S.; Validation, G.S. and L.C.F.M.B.; Formal analysis, J.S.M.R.; Investigation, G.C.C. and L.A.S.; Original draft preparation, J.S.M.R. and G.S.; Review and editing, C.G.S., R.G.B and L.C.F.M.B.; Visualization, L.C.F.M.B.; Supervision, J.S.M.R., L.C.F.M.B. and G.S.; Funding acquisition, L.C.F.M.B. and G.S.

CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

DISCLOSURE OF ARTIFICIAL INTELLIGENCE ASSISTANCE

The authors acknowledge the use of artificial intelligence tools in the preparation of this manuscript. Specifically, ChatGPT by OpenAI was utilised to support linguistic refinement. All AI-assisted content was carefully reviewed, edited, and validated by the authors to ensure scholarly integrity, originality, and compliance with ethical standards. The authors affirm full responsibility for the content of the manuscript, including any material generated or supported by artificial intelligence.



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Estimating the Process Sigma Level Based on Information from Statistical Process Control or Process Capability Analysis

DOI: 10.12776/qip.v30i1.2335

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Received: 14-2-2026 Accepted: 18-3-2026 Published: 30-4-2026

ABSTRACT

Purpose: The article proposes an approach to estimating the process sigma level based on information from statistical process control or process capability analysis.

Methodology/Approach: The z -score for each critical-to-quality characteristic and for the overall process is estimated from the data obtained in statistical process control or process capability analysis.

Findings: The proposed procedure for estimating the sigma level offers several advantages over the traditional method.

Research Limitation/Implication: We assume that each critical-to-quality characteristic is linked to only one type of defect opportunity, which can result in only one defect of that type on a single unit. We only consider continuous, normally distributed, and nominal critical-to-quality characteristics with two possible values: non-defective and defective.

Originality/Value of paper: The proposed procedure enables us to use information from statistical process control and process capability analysis to estimate the process sigma level and provides additional valuable insights into the process.

Category: Research paper

Keywords: process sigma level; critical-to-quality characteristic; defect; defect opportunity

Research Areas: Quality Engineering

1 INTRODUCTION

The article proposes an alternative method for estimating the process sigma level (z -score) that offers several benefits over the traditional procedure.

If the process is measurably incapable and variability is the dominant problem, statistical process control (SPC) is typically applied to understand and stabilise variability. Once the process is stabilised, the process capability is estimated, often using process capability indices. Utilising both SPC and capability indices requires estimating the probability distribution parameters of the quality characteristics. If SPC indicates that routine control measures are inadequate or if the process capability indices are low, it may prompt consideration of a Six Sigma project. These are just two potential reasons to initiate a Six Sigma project within an organisation; there can be other specific quantitative and qualitative factors that lead to this decision.

The Six Sigma approach is project-oriented and focused on the organisation's strategic business goals. The primary purpose of the Six Sigma project is to address a specific problem and contribute to achieving the organisation's business objectives. The fundamental philosophy is centred around increasing customer satisfaction by eliminating and preventing nonconformities, ultimately leading to increased business profitability (Zgodavová et al., 2020). The primary advantage of this methodology is its rigorous approach to identifying and eliminating sources of variability (Stamatis, 2003, p. 9). Six Sigma activities are associated with the DMAIC procedure, which comprises five phases: Define, Measure, Analyse, Improve, and Control. In the define phase, the problem to be addressed is identified and clearly defined. The measure phase focuses on measuring the current performance of the process to be improved. In the analysis phase, the main causes of poor performance are identified. The improvement phase aims to test and evaluate potential solutions to create a robust, improved process. In the control phase, improved processes are monitored through standardized procedures that can be operated and continuously refined, ensuring that performance improvements are sustained over time. The DMAIC is widely used to reduce defects, minimize variation, and enhance process capability.

Six Sigma indicators are measurable metrics utilized to evaluate the performance and progress of Six Sigma projects and processes. Key metrics include Defects per Opportunity (DPO), Defects Per Million Opportunities (DPMO), and Defects per Unit (DPU) (Costa et al., 2019). The first step in initiating a Six Sigma project is to estimate the process sigma level using the DPMO metric. Traditionally, DPMO is estimated from a random sample of products, and the result is then used to determine the process's z -score.

When implementing statistical process control, it is essential to estimate the means and standard deviations of continuous characteristics. During capability analysis, these parameters must also be estimated when calculating the C_{pk} capability index. For nominal characteristics, the proportion of defective units is estimated, instead

of these parameters. Once the estimates of these parameters are available, they can also be used to calculate DPMO and the z -scores for individual characteristics, as well as the overall z -score for the product manufacturing process. Therefore, selecting a new sample is unnecessary.

We will begin with the method for calculating the DPMO characteristic and the capability indices C_p and C_{pk} . We will show how to calculate DPMO and the corresponding sigma level for individual characteristics and for the entire process. This will use the estimated distribution parameters of the critical-to-quality characteristics obtained during the implementation of statistical process control or process capability analysis. To clarify this calculation procedure, we will illustrate it with an example.

2 LITERATURE REVIEW

When assessing a single product, multiple critical-to-quality characteristics are typically monitored. The sigma level (z -score) for different critical-to-quality characteristics is determined based on the DPMO indicator value. Its value is usually estimated from a random sample by the value of the sample \widehat{DPMO} , calculated as follows (ISO 13053 – 1 (2011)):

$$\widehat{DPMO} = \frac{c}{n_{\text{units}} \cdot n_{\text{CTQC}}} \cdot 1,000,000 = \widehat{DPO} \cdot 1,000,000 \quad (1)$$

where \widehat{DPMO} is the sample number of defects per million opportunities,
 c is the number of defects in the sample,
 n_{units} is the sample size,
 n_{CTQC} is the number of critical-to-quality characteristics,
 $n_{\text{units}} \cdot n_{\text{CTQC}}$ are the number of defect opportunities in the sample,
 \widehat{DPO} is the sample number of defects per opportunity.

Based on this value, the process sigma level (z -score) is determined (see, for example, ISO 13053-1, 2011; Terek, 2023).

Six Sigma is closely linked with process capability analysis. One of the process capability analysis tools is the capability indices. Let us consider a characteristic X with a normal distribution, mean μ , and standard deviation σ . When calculating capability indices, it is assumed that the process is stable, the observations are statistically independent, and they follow a normal distribution. The basic capability index C_p is defined as:

$$C_p = \frac{USL - LSL}{6\sigma} \quad (2)$$

where USL is the upper specification limit,

LSL is the lower specification limit,

σ is the standard deviation of the characteristic.

A disadvantage of this index is that it does not allow assessment of process centring – the distance of the process mean μ from the midpoint of the specifications. Therefore, it is considered only a measure of potential process capability (Montgomery, 2020, p. 328).

Unlike the C_p index, the C_{pk} index responds to a shift of the process mean from the midpoint of the specifications. It is calculated as:

$$C_{pk} = \min(C_{pu}, C_{pl}), \text{ where } C_{pu} = \frac{USL - \mu}{3\sigma}; \quad C_{pl} = \frac{\mu - LSL}{3\sigma} \quad (3)$$

Unlike C_p , which is an indicator of potential process capability, C_{pk} is an indicator of actual process capability because it responds to the deviation of the process mean μ from the midpoint of the specifications in the case of a two-sided interval. The parameters μ and σ are usually unknown and need to be estimated by point estimates $\hat{\mu}$ and $\hat{\sigma}$. The estimated values \hat{C}_p and \hat{C}_{pk} are then obtained by replacing μ and σ in equations (2) and (3) with their point estimates $\hat{\mu}$ and $\hat{\sigma}$ (Terek & Hrnčiarová, 2004; Benková, Bednářová, & Bogdanovská, 2024; Montgomery, 2020; Tošenovský & Tošenovský, 2019).

Let the characteristic X have a normal distribution with a mean of μ_0 at the midpoint of the specifications (the process is ideally centred) and a standard deviation of σ . Then the upper and lower specification limits, USL and LSL, are:

$$USL = \mu_0 + z\sigma \quad (4)$$

$$LSL = \mu_0 - z\sigma \quad (5)$$

where z is the value of the random variable Z with a standard normal distribution and determines the distance of USL and LSL from the midpoint of the specifications μ_0 , measured in standard deviations σ . The value of z also determines the sigma level (z -score). A corresponding DPMO value is associated with each z value. When calculating it, a shift of the process mean from the midpoint of the specifications by 1.5σ to the right or left is assumed.

There is a relationship between the z -score and the C_{pk} index. Let us first consider ideal centring of the characteristic at the midpoint of the specifications (the so-called short-term view). Then, C_{pu} and C_{pl} represent the distance of USL and LSL from the midpoint of the specifications, measured in standard deviations σ , divided by three, so: $C_{pk} = C_{pu} = C_{pl} = z/3$. For an ideally centred process, $C_{pk} = C_p$. When

considering a shift of the characteristic mean by 1.5 standard deviations to either the right or left (long-term view), then $C_{pk} = (z - 1.5)/3$.

The Sigma to DPMO, Yield to C_{pk} tables, and the Six Sigma Conversion Table show the corresponding values of DPMO, z -score, and C_{pk} for a short-term view in the rows. Chen, Ouyang, Hsu, & Wu (2009) explain the relationship between the z -score and C_{pk} , considering both scenarios: when the process is centred within the specification range and when the process mean shifts by 1.5σ to the right or left.

To estimate the z -score, an approach in which C_{pk} is calculated for a characteristic based on relations (3), and then the z -score is computed using the formula $z = 3C_{pk} + 1.5$, can be used. This method can be applied when estimating the z -score for individual characteristics only, but not when estimating the z -score for the entire process. Another limitation of this approach is that capability indices are not calculated for nominal characteristics.

3 METHODOLOGY

Only continuous and nominal critical-to-quality characteristics (CTQCs) will be considered in a process. We assume that the continuous ones follow a normal distribution with a mean μ and standard deviation σ , while the nominal ones can take on two values: non-defective and defective. Nonconformity is defined as non-fulfilment of a requirement, and defect is defined as non-fulfilment of a requirement related to an intended or specified use (ISO 3534-2, 2014). In this article, each nonconformity – i.e., non-compliance of the value of a critical-to-quality characteristic with the requirements (specified specification limits or performance standards) – is considered a defect¹. A defect opportunity is any measurable event creating a possible defect (ISO 13053-2, 2011). We assume that each critical-to-quality characteristic is associated with only one type of defect opportunity.

We consider n_{CTQC} critical-to-quality characteristics. The production of a single unit provides n_{CTQC} distinct defect opportunities. The i -th critical-to-quality characteristic creates the defect opportunity of type i . One defect opportunity of type i can result in only one defect of type i on a single unit.

When implementing statistical process control of the characteristic, and when calculating the process capability index C_{pk} , it is essential to estimate the mean and standard deviation of the continuous characteristic when the process is stable. Using them, we estimate the z -score for each continuous critical-to-quality characteristic. The z -score for each nominal critical-to-quality characteristic is

¹ We will assume that any non-compliance of the value of a critical-to-quality characteristic with the requirements will affect the functionality or safety of the product.

estimated from the sample proportion of defective units. Finally, the z -score for the overall process is estimated.

4 PROCEDURE FOR ESTIMATING SIGMA LEVEL FOR CTQCs AND THE ENTIRE PROCESS

Let us first consider only one critical-to-quality characteristic. The DPU in the population is the probability that a unit is defective (the proportion of defective units, the number of defective units per unit). The DPO in the population is the probability that a defect opportunity generates a defect (the proportion of opportunities generating a defect, the number of opportunities that generate a defect per opportunity). When we consider only one critical-to-quality characteristic (continuous or nominal), each unit provides one defect opportunity, and $DPU = DPO$.

Suppose that the mean of a continuous characteristic X with a normal distribution is shifted from the midpoint of the specifications μ_0 by k standard deviations σ :

$$\mu = \mu_0 + k\sigma$$

where k is the distance of μ from μ_0 measured in standard deviations σ . We calculate the probability that the unit is non-defective:

$$P(LSL \leq X \leq USL)$$

Next, we will standardise USL and LSL:

$$z_{USL} = \frac{\mu_0 + z\sigma - (\mu_0 + k\sigma)}{\sigma} = z - k$$

$$z_{LSL} = \frac{\mu_0 - z\sigma - (\mu_0 + k\sigma)}{\sigma} = -(z + k)$$

where z_{USL} , z_{LSL} are the values of the random variable Z with the standard normal distribution. Apparently:

$$P(LSL \leq X \leq USL) = P(z_{LSL} \leq Z \leq z_{USL}) = \Phi(z - k) - 1 + \Phi(z + k)$$

where Φ is the distribution function of the standard normal distribution. The probability that a unit is defective is:

$$DPU = P(X \leq LSL) + P(X \geq USL) = 1 - P(LSL \leq X \leq USL) = 2 - \Phi(z - k) - \Phi(z + k) \tag{6}$$

Since we consider only one characteristic, $DPU = DPO$, when the number of defects per opportunity is multiplied by 1,000,000, we obtain the number of defects per million opportunities (DPMO).

In the Six Sigma concept's design, it is assumed that the process mean can shift from the target value by 1.5 standard deviations, either to the right or left. This

model serves as a standard for comparing process performance based on z -score across various critical-to-quality characteristics. ISO 13053-1(2011) includes Table A.1 — Sigma scores, which presents calculated DPMO values for process sigma levels from 0 to 6, in increments of 0.01. These values are based on the probability of a unit being defective in relation to the upper specification limit only² (for further details, see Terek, 2023):

$$\begin{aligned} \text{DPO} &= P(X \geq \text{USL}) = P\left(Z \geq \frac{\mu_0 + z\sigma - (\mu_0 + 1.5\sigma)}{\sigma}\right) = 1 - P(Z \leq (z - 1.5)) = \\ &= 1 - \Phi(z - 1.5) \end{aligned}$$

We will assume that if the critical-to-quality characteristic is continuous, it has a normal distribution, and we know its estimated mean and estimated standard deviation. If it is a nominal one, we assume that we know its estimated proportion of defective units.

First, we will consider each critical-to-quality characteristic separately. For each of them, we will find the sigma level. We will proceed as follows:

1. If the critical-to-quality characteristic is continuous, we will proceed to step 2; if it is nominal, we will proceed to step 3.
2. We will calculate the distance of each of the specification limits from the midpoint of the specifications, measured in standard deviations, and the deviation of the mean of the characteristic from the midpoint of the specifications, measured in standard deviations. We will substitute the calculated values in relation (6) for z and k and calculate the estimated DPO. We will proceed to step 4.
3. We will estimate the DPO value by the estimated value of the proportion of defective units and proceed to step 4.
4. From the estimated DPO, we will calculate the estimated DPMO value and determine the z -score from it.

Finally, we will estimate the sigma level of the entire process by using the estimated DPOs of each critical-to-quality characteristic.

Consider $n_{\text{CTQC}} > 1$ critical-to-quality characteristics. Let DPO_i be the probability that a defect opportunity of type i results in a defect of type i . The types of opportunity are equally numerous, because each type occurs on all units. Then $\text{DPO}_i/n_{\text{CTQC}}$ is the probability that a defect opportunity of any type results in a defect of type i .

The events “a defect of type i will occur” for $i = 1, 2, \dots, n_{\text{CTQC}}$ are disjoint, because we are considering opportunities, not units. One defect opportunity of type i can result in only one defect of type i . Then we can calculate the probability that a

² The results in Table A1 differ only slightly from the results obtained by calculating the probability that a unit is defective according to equation (6), for $k = 1.5$.

defect opportunity of any type results in a defect of any type simply as a sum of probabilities, as follows:

$$DPO = \sum_{i=1}^{n_{CTQC}} DPO_i/n_{CTQC} \tag{7}$$

After multiplying DPO by 1,000,000, we get DPMO as the number of defects per million opportunities for the entire process, from which the *z*-score of the entire process is determined. The procedure will be demonstrated using an example from ceramic capacitor production.

Example. Ceramic capacitors are being manufactured, and we consider three critical-to-quality characteristics:

X_1 represents capacitance (μF), which indicates the ability to store electric charge. It is a continuous variable with specification limits: $LSL = 9.5 \mu\text{F}$ and $USL = 10.5 \mu\text{F}$. The midpoint of the specifications is $\mu_0 = 10 \mu\text{F}$. In the process capability analysis, it was determined that the distribution of the variable X_1 is approximately normal. The estimated mean is $\hat{\mu}_1 = 10.2 \mu\text{F}$, with an estimated standard deviation of $\hat{\sigma}_1 = 0.1 \mu\text{F}$. The mean is shifted $0.2 \mu\text{F}$ to the right of the midpoint of the specifications.

When substituting the values 9.5 and 10.5 for LSL and USL, respectively, $\hat{\mu}_1 = 10.2$ for μ and $\hat{\sigma}_1 = 0.1$ for σ into relations (2) and (3), we obtain:

$$\hat{C}_p = 1.667; \hat{C}_{pk} = 1$$

X_2 – equivalent series resistance (Ω) – a continuous variable with specification limits $LSL = 0.08 \Omega$, $USL = 0.12 \Omega$, with the midpoint of the specifications $\mu_0 = 0.1 \Omega$. The distribution of the variable X_2 is approximately normal; the estimated mean is $\hat{\mu}_2 = 0.095 \Omega$, and the estimated standard deviation is $\hat{\sigma}_2 = 0.01 \Omega$. The mean of the variable shifts 0.005Ω to the left of the midpoint of the specifications.

When substituting the values 0.08 and 0.12 for LSL and USL, respectively, $\hat{\mu}_2 = 0.095$ for μ and $\hat{\sigma}_2 = 0.01$ for σ into relations (2) and (3), we obtain:

$$\hat{C}_p = 0.667; \hat{C}_{pk} = 0.5$$

X_3 – dimensions (width \times height \times length) (mm) – $3.2 \pm 0.2 \text{ mm} \times 1.6 \pm 0.2 \text{ mm} \times 1.5 \pm 0.1 \text{ mm}$. The dimensions are critical for mounting the ceramic capacitor on a printed circuit board. Compliance with the dimensional specification – a nominal variable with values “non-defective” when all dimensions are within specifications, and “defective” when at least one dimension is out of specification. From a random sample, the sample proportion of defective units was calculated as $\hat{p} = 0.023$.

We will determine the *z*-score for each of the three characteristics and for the overall ceramic capacitor manufacturing process. In Six Sigma practice, results are

usually rounded to four or five decimal places. However, intermediate results used in other formulas, such as the calculation of the sigma score, are not rounded.

1. We will determine the z -score for X_1

First, we will calculate z_1 and k_1 , where z_1 is the distance of each specification limit X_1 from the midpoint of the specifications, measured in standard deviations $\hat{\sigma}_1$, and k_1 is the distance $\hat{\mu}_1$ from μ_0 , measured in standard deviations $\hat{\sigma}_1$.

$$z_1 = \frac{\mu_0 - \text{LSL}}{\hat{\sigma}_1} = \frac{10 - 9.5}{0.1} = 5$$

$$k_1 = \frac{\hat{\mu}_1 - \mu_0}{\hat{\sigma}_1} = \frac{10.2 - 10}{0.1} = 2$$

After substituting z_1 and k_1 for z and k in (6), we get:

$$\widehat{\text{DPO}}_1 = 2 - \Phi(z_1 - k_1) - \Phi(z_1 + k_1) = 2 - \Phi(5 - 2) - \Phi(5 + 2) = 2 - \Phi(3) - \Phi(7) = 2 - 0.998650102 - 1 = 0.001349898$$

of which:

$$\widehat{\text{DPMO}}_1 = \widehat{\text{DPO}}_1 \cdot 1,000,000 \approx 1\,350.$$

In ISO 13053-1 (2011), on page 28, there is Table A.1 – Sigma scores. Based on a DPMO value of 1350, the z -score is approximately 4.5 (according to Table A.1). There is also an alternative method to determine the z -score. We know that:

$$1 - \widehat{\text{DPO}}_1 = \Phi(z - 1.5)$$

After substituting 0.001349898 for $\widehat{\text{DPO}}_1$ in the last relation, we get:

$$0.998650102 = \Phi(z - 1.5) = \Phi(z_{0.998650102})$$

Using the NORM.S.INV function in Excel, we find $z_{0.998650102} \approx 3$. Then $(z - 1.5) \approx 3$, which gives us $z \approx 4.5$. The sigma score for the process with respect to ceramic capacitor capacitance is approximately 4.5.

2. Let's calculate the z -score for X_2

First, we calculate z_2 and k_2 , where z_2 is the distance of each of the specification limits of X_2 from the midpoint of the specifications, measured in standard deviations $\hat{\sigma}_2$, and k_2 is the distance of $\hat{\mu}_2$ from μ_0 , measured in standard deviations $\hat{\sigma}_2$.

$$z_2 = \frac{\mu_0 - \text{LSL}}{\hat{\sigma}_2} = \frac{0.1 - 0.08}{0.01} = 2$$

$$k_2 = \frac{\hat{\mu}_2 - \mu_0}{\hat{\sigma}_2} = \frac{0.095 - 0.1}{0.01} = -0.5$$

After substituting z_2 and k_2 for z and k in (6), we get:

$$\widehat{DPO}_2 = 2 - \Phi(z_2 - k_2) - \Phi(z_2 + k_2) = 2 - \Phi(2 + 0.5) - \Phi(2 - 0.5) = 2 - \Phi(2.5) - \Phi(1.5) = 2 - 0.993790335 - 0.933192799 = 0.073016866$$

$$\widehat{DPMO}_2 = \widehat{DPO}_2 \cdot 1,000,000 \approx 73,017$$

When finding the z -score, we put:

$$1 - \widehat{DPO}_2 = \Phi(z - 1.5)$$

After substituting 0.073016866 for \widehat{DPO}_2 in the last relation, we get:

$$0.926983134 = \Phi(z - 1.5) = \Phi(z_{0.926983134})$$

Using the NORM.S.INV function in Excel, we find $z_{0.926983134} \approx 1.45$. Then $(z - 1.5) \approx 1.45$, which gives us $z \approx 2.95$. The same result you can also find at ISO 13053-1 (2011), Table A.1 – Sigma scores for $\widehat{DPMO}_2 = 73,017$. The sigma score of the process with respect to the equivalent series resistance is approximately 2.95.

3. We calculate the z -score for X_3

The third characteristic is the conformity to the dimensional specification – a nominal variable with values of “non-defective” when all dimensions are within specification, “defective” when at least one dimension is not within specification.

For nominal variables, capability indices are not calculated. The sample proportion of defective units, $\hat{p} = 0.023$, was calculated from the random sample. We can write:

$$\widehat{DPO}_3 = \hat{p} = 0.023 \text{ and } \widehat{DPMO}_3 = 23,000$$

When finding the z -score, we put:

$$1 - \widehat{DPO}_3 = \Phi(z - 1.5)$$

After substituting 0.023 for \widehat{DPO}_3 in the last relation, we get:

$$0.977 = \Phi(z - 1.5) = \Phi(z_{0.977})$$

Using the NORM.S.INV function in Excel, we find $z_{0.977} \approx 1.995$. Then $(z - 1.5) \approx 1.995$, which gives us $z \approx 3.5$.

The sigma score of the process with respect to the conformity to the dimensional specification is approximately 3.5. The same result you can also find at ISO 13053-1 (2011), Table A.1 – Sigma scores for $\widehat{DPMO}_3 = 23,000$.

We will now calculate the estimated sigma level of the entire ceramic capacitor production process, with three critical-to-quality characteristics. We will calculate according to relation (7):

$$\widehat{DPO} = \sum_{i=1}^{n_{CTQC}} \widehat{DPO}_i / n_{CTQC} = \frac{0.001349898 + 0.073016866 + 0.023}{3} = 0.032455588$$

Of which:

$$1 - \widehat{DPO} = 0.967544412$$

When finding the z -score, we put:

$$1 - \widehat{DPO} = \Phi(z - 1.5)$$

After substituting 0.032455588 for \widehat{DPO} in the last relation, we get:

$$0.967544412 = \Phi(z - 1.5) = \Phi(z_{0.967544412})$$

Using the NORM.S.INV function in Excel, we find $z_{0.967544412} \approx 1.84587$. Then $(z - 1.5) \approx 1.84587$, which gives us $z \approx 3.35$. The same result you can also find at ISO 13053-1 (2011), Table A.1 - Sigma scores for $\widehat{DPMO} = 32,456$.

For illustration, let us assume that we have proceeded traditionally. We have randomly selected, say, 1,000 units and found the number of defects of the first to third type in accordance with the estimated $\widehat{DPO}_i - 1, 73$ and 23. After substitution in (1), we get:

$$\widehat{DPMO} = [(1 + 73 + 23)/(1,000 \cdot 3)] \cdot 1,000,000 \approx 32,333$$

In ISO 13053-1 (2011), Table A.1 – Sigma scores, we find that the corresponding $z \approx 3.35$. We obtained the same result as when applying the proposed method.

When determining the z -score based on the estimated DPMO, we use a standard model that assumes a shift of the process mean by 1.5 standard deviations to the right from the midpoint of the specifications and considers only the upper specification limit. This is not inconsistent with the procedure for calculating DPO and DPMO, which considers the actual shift in the mean.

Let us consider X_1 . From the point of view of process performance, it is ultimately irrelevant whether the value \widehat{DPO}_1 is achieved with a shift of the mean by two standard deviations to the right, combined with a smaller variance, or whether we consider a theoretical model that assumes a change in the mean by 1.5 standard deviations to the right with a larger variance. Originally, the estimated values were $\hat{\mu}_1 = 10.2 \mu\text{F}$ and $\hat{\sigma}_1 = 0.1 \mu\text{F}$. The estimated mean of the characteristic is shifted from the midpoint of the specifications $\mu_0 = 10 \mu\text{F}$, by two standard deviations to the right. The value $\widehat{DPO}_1 = 0.001349898$. If we consider the model situation – a shift of the mean by 1.5 standard deviations to the right – then for $\hat{\mu}_1 = 10.16667 \mu\text{F}$ and $\hat{\sigma}_1 = 0.11111 \mu\text{F}$ (the mean is shifted from 10 to the right by $1.5 \cdot 0.11111 = 0.166665$), we obtain, according to relation (6), approximately the same value

\widehat{DPO}_1 . With a smaller shift of the mean, we would obtain the same \widehat{DPO}_1 value for a larger standard deviation.

A similar interpretation applies to variable X_2 in the example. Originally, the measured values were $\hat{\mu}_2 = 0.095 \Omega$ and $\hat{\sigma}_2 = 0.01 \Omega$. The estimated mean of the characteristic is shifted from the midpoint of the specifications $\mu_0 = 0.1 \Omega$, by 0.5 standard deviations to the left. The value $\widehat{DPO}_2 = 0.073016866$. If we consider the model situation – a shift of the mean by 1.5 standard deviations to the left – then for $\hat{\mu}_2 = 0.089830509 \Omega$ and $\hat{\sigma}_2 = 0.006779661 \Omega$ (the mean is shifted from 0.1 to the left by $1.5 \cdot 0.006779661 = 0.010169491$), we obtain, according to relation (6), approximately the same \widehat{DPO}_2 . With a larger shift of the mean, we would obtain the same \widehat{DPO}_2 value for a smaller standard deviation. Variable X_3 is nominal, and the sample proportion value can be used to estimate DPO_3 . The theoretical model serves as a standard for comparing the performance of different processes using the z -score.

In the example, the process sigma score with respect to the capacitance of the ceramic capacitor is approximately 4.5, with respect to the equivalent series resistance it is approximately 2.95, and with respect to compliance with the dimensional specification it is approximately 3.5. The sigma score of the entire ceramic capacitor production process is approximately 3.35. This indicates that the “weakest point” of the ceramic capacitor manufacturing process is compliance with the specification limits for the equivalent series resistance. The proposed method thus enables improving priority setting and planning of Six Sigma projects.

5 CONCLUSIONS

The article aimed to propose a procedure for using parameter estimates of the distribution of critical-to-quality characteristics obtained from statistical process control or process capability analysis, when estimating the process sigma level for individual critical-to-quality characteristics, as well as for the entire product production process. The proposed procedure allows this estimation to be performed using estimates of the means and standard deviations of continuous characteristics and estimates of proportions of defective units of nominal characteristics.

The given method effectively estimates the z -score for both individual characteristics and the overall process, accounting for both continuous and nominal critical-to-quality characteristics. The benefit of this procedure is that another random sample is not needed to estimate the DPMO. Another advantage of the proposed procedure is that the DPO, DPMO, and z -score estimates can be obtained for each characteristic immediately after estimating the respective means, standard deviations, and proportions. Then, a simple method enables us to determine the DPO, DPMO, and z -score estimates for the entire production process. This is important information for decision-making whether to develop a Six Sigma

project for the product production process and, if so, which characteristics have a low z -score and should be addressed as a priority in the project.

When implementing statistical process control or determining process capability, the means and standard deviations for continuous characteristics and the proportions of defective units for nominal critical-to-quality characteristics are estimated. It would be a shame not to immediately use this information to estimate their z -score, because these estimates can be very helpful in finding processes suitable for Six Sigma projects and in structuring them.

ACKNOWLEDGEMENTS

The author expresses gratitude to the Vysoká škola manažmentu/City University of Seattle for its comprehensive support of his research activities.

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CONFLICTS OF INTEREST

The author declares that he has no conflict of interest. The funders had no role in the design of the study, the collection, analysis, or interpretation of data, the writing of the manuscript, or the decision to publish the results.

DISCLOSURE OF ARTIFICIAL INTELLIGENCE ASSISTANCE

The author acknowledges the use of artificial intelligence tools in the preparation of this manuscript. Specifically, ChatGPT was utilised to support linguistic refinement and drafting of non-analytical sections. All AI-assisted content was carefully reviewed, edited, and validated by the author to ensure scholarly integrity, originality, and compliance with ethical standards. The author affirms full responsibility for the content of the manuscript, including any material generated or supported by artificial intelligence.



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Legal Model of Conservation in the Galápagos Islands: Replicable Lessons for Sustainability

DOI: 10.12776/qip.v30i1.2340

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Received: 18-02-2026 Accepted: 13-04-2026 Published: 30-04-2026

ABSTRACT

Purpose: To analyse, from a comparative perspective, the factors that determine the effectiveness of environmental conservation and enforcement mechanisms, as well as their application in the case of the Galápagos Archipelago.

Methodology/Approach: A comparative approach was used based on experiences from Asia, Europe, and Latin America, considering operational metrics, governance mechanisms, and enforcement systems.

Findings: Effective conservation is based on three pillars: zoning with effort limits, multilevel governance, and precautionary enforcement mechanisms with adaptive management. Social legitimacy, meaningful participation, and the use of operational metrics are key factors in closing the gap between regulations and outcomes. The Galápagos emerges as a robust model by integrating zoning, biosecurity, and the regulation of tourism and fisheries through transparency and public monitoring. Challenges persist related to dependence on tourism, pressure from invasive species, and asymmetries in enforcement.

Research Limitation/Implication: Structural challenges persist, related to dependence on tourism, pressure from invasive species, and asymmetries in enforcement.

Originality/Value of paper: The paper proposes adjustments aimed at standardising precautionary thresholds, strengthening open data and audits, diversifying funding sources, and consolidating local technical capacities.

Category: Conceptual paper

Keywords: Galápagos Islands; conservation; zoning; biosecurity

Research Areas: Quality by Sustainability

1 INTRODUCTION

Conservation laws are central to safeguarding humanity's natural and cultural heritage. The 1972 Convention concerning the Protection of the World Cultural and Natural Heritage adopted by the United Nations Educational, Scientific and Cultural Organization establishes state obligations to protect properties of outstanding universal value through legal, administrative, scientific, and financial measures and international cooperation, while UNESCO's recent biodiversity commitments stress the need for regulatory frameworks integrating conservation, sustainable use, local and Indigenous knowledge, and social equity in response to climate change and species loss (UNESCO, 1972; UNESCO, 2025).

Comparative evidence confirms that designation alone is insufficient. In the Mediterranean, the MaPAF framework combines legal and management indicators to assess real protection outcomes, and in Russia Federal Law No. 33 FZ balances conservation with development and local rights (Rodríguez, Rodríguez, & Abdul, 2016; Massé, 2019). In China, Indonesia, Vietnam, and India, reforms emphasise zoning, multilevel governance, regulatory clarity, and local capacity to align conservation with development needs (Nikolaychuk, 2023; Lü, 2019; Lubis, 2017; Nugraha, Febrian, & Chen, 2020). Island microstates such as Seychelles confront fragmentation but advance integrated ocean governance through blue economy frameworks (Saddington, 2023). In Europe, greater coherence among objectives, zoning, and enforcement improves outcomes, though overlaps remain, particularly in England (Dardi & Shanthakumar, 2023; Puritz & Hill, 2020).

In Latin America, Colombia's constitutional anchoring strengthens environmental governance, while Brazil's experience with oceanic archipelagos highlights the need for harmonized legal categories and innovative tools such as legal personality for protected areas (Munévar & Ramírez, 2021). Ecuador's ACUS model in Santo Domingo shows how special regimes and prioritization methodologies can operationalize conservation mandates (Calva, Cacpata, & Montece, 2022). These cases underscore the regional challenge of translating constitutional principles into binding and workable mechanisms.

Within this comparative landscape, the Galápagos Archipelago operates as an exceptional ecological legal laboratory. Its constitutional special regime under Article 258, developed through LOREG and the Galápagos National Park planning instruments, integrates zoning, biosecurity, fisheries regulation, tourism control, and community participation. The Galápagos Protected Areas Management Plan for Buen Vivir embeds precaution, rights of nature, and restoration within a dedicated institutional structure led by the Governing Council and the National Park Directorate. By linking environmental protection and human development under the paradigm of Buen Vivir or Sumak Kawsay, the Galápagos model represents a distinctive framework of integrated and operational conservation (Figure 1).

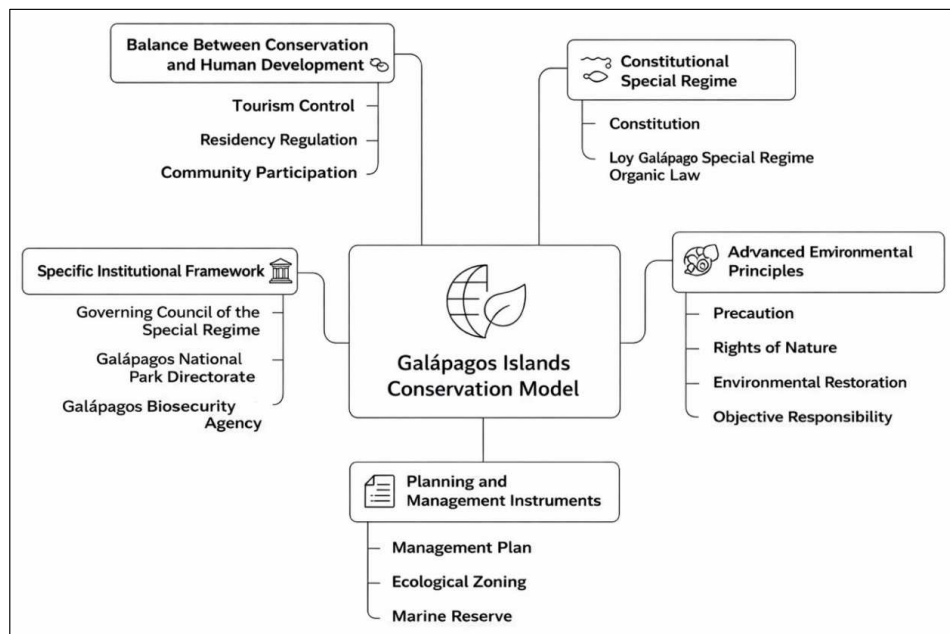


Figure 1 – Conservation model of the Galápagos Islands

However, the challenge is not exclusively normative, as a solid legal architecture does not by itself ensure effective conservation outcomes. In this regard, certain legal and institutional elements function as friction creators, namely limits, controls, and procedures that slow harmful activities and guide behaviour toward sustainability in the face of recurrent pressures such as tourism, fishing, and biological invasions. It is therefore essential to identify which instruments, such as zoning, biosecurity, effort limits, and sanctions, demonstrate greater coherence and effectiveness, how they are articulated with adaptive management, and what lessons can be extrapolated to other island and coastal marine territories in Latin America (UNESCO, 1972; Rodríguez et al., 2016; Massé, 2019).

In this sense, an analysis of the Galápagos legal conservation model makes it possible to identify transferable strategies and lessons for other countries and for insular and coastal marine contexts. The objective of this study is to critically examine this model in terms of its normative design and implementation, extract replicable conservation lessons, and propose improvement strategies that can be incorporated into the current Galápagos framework. The analysis considers enabling governance conditions such as internormative coherence, multilevel coordination, and the existence of effective management metrics, together with legitimacy safeguards grounded in substantive participation and democratic oversight, in order to prevent the drift toward paper parks and to orient instruments such as zoning, biosecurity, effort limits, and sanctioning regimes toward verifiable and socially accepted ecological outcomes.

2 METHODOLOGY

This study adopts a legal dogmatic approach through a case study of the special regime of the Galápagos Islands, aimed at interpreting and systematising the regulatory framework governing conservation in a territory marked by high ecological sensitivity and significant anthropogenic pressure. The analysis consists of a critical review of legal norms, principles, and doctrine to assess their internal coherence and practical applicability in environmental governance. The analytical corpus includes the 2008 Constitution, the Organic Law of the Special Regime of the Province of Galápagos (LOREG), its implementing regulations, current management plans, specialised doctrine, constitutional and administrative case law, and official reports, selected based on validity, normative relevance, and applicability to the insular context.

The study proceeds at three complementary levels. First, it evaluates vertical and horizontal coherence, examining alignment among constitutional, legal, regulatory, and planning instruments, as well as intersectoral consistency among environmental, tourism, and local development policies, considering their evolution between 2008 and 2030. Second, it maps institutional competencies by identifying mandates, gaps, overlaps, and operational capacity in terrestrial and marine protected areas. Third, it incorporates a policy-oriented comparative analysis contrasting the Ecuadorian framework with insular and coastal marine conservation regimes in other jurisdictions, using criteria such as zoning, multilevel governance, compliance metrics, social legitimacy, and transparency.

Evaluation is guided by criteria of normative coherence, enforcement effectiveness, ecological adequacy in relation to conservation objectives and carrying capacity, legitimacy and participation through social oversight, and transparency, emphasising open data, audits, and public reporting. The strategy is strictly documentary, based on systematic interpretation, normative comparison, and triangulation of legal texts, doctrine, jurisprudence, and official statistics. Limitations include potential source bias, uneven data quality, and conditional transferability due to the singular nature of the Galápagos regime; these are mitigated through comprehensive documentary analysis, comparative perspective, and a longitudinal assessment of regulatory evolution.

3 DEVELOPMENT

3.1 Rights of nature, the precautionary principle, and their operation in protected areas

The Constitution of the Republic of Ecuador (2008) represents a milestone in environmental constitutionalism. Articles 71 to 74 recognise Nature as a subject of rights, guaranteeing its existence, persistence, and regeneration, and empower individuals and communities to demand their enforcement, consolidating a biocentric vision inspired by Andean cosmology. Complementarily, Article 73

establishes the precautionary principle, which requires the adoption of preventive measures even under conditions of scientific uncertainty, prioritising the protection of ecological functions and applying the rule in dubio pro natura as an interpretive criterion (Lozano, 2023; Astudillo & Maldonado, 2025).

This recognition is not merely declaratory but constitutes a binding mandate that reconfigures the legal order. The protection of Pachamama acquires the status of a public duty and a substantive limit on public and private decision-making. Within this framework, the precautionary principle functions as a key instrument for preventing serious or irreversible damage under scientific uncertainty, while the right to restoration imposes an obligation of full environmental remediation. The convergence of these elements is particularly relevant in the management of natural protected areas, which constitute the core of national and global biodiversity (Barahona & Añazco, 2020; Garate et al., 2024).

Protected areas cover nearly 20 per cent of the national territory and include national parks, ecological reserves, and wildlife refuges. In these areas, the operationalisation of the Rights of Nature, precaution, and restoration is articulated through the National System of Protected Areas (SNAP), designed to ensure biodiversity conservation, the maintenance of ecological functions, and the collective enjoyment of ecosystem services. Any policy or intervention in these spaces must be subject to reinforced constitutional protection, with strict standards of prevention, mitigation, and remediation (Sandoval, Galarraga, & Galarraga, 2021).

This normative framework is integrated with the paradigm of Buen Vivir (Sumak Kawsay), a guiding constitutional principle that directs public action toward the harmonious integration of society, the economy, and ecological integrity. In protected areas, this requires management decisions that incorporate intergenerational justice, substantive participation of local and Indigenous communities, and territorial equity, so that conservation becomes the foundation of human development compatible with ecological limits. However, the coexistence of an extractive development model with the biocentric mandate undermines the effectiveness of precautionary and restoration principles and weakens public trust. Overcoming these gaps requires strengthening monitoring and social oversight mechanisms, ensuring transparency in environmental information, promoting effective interinstitutional coordination, and fostering citizen participation with real decision-making capacity, in line with the objectives of Buen Vivir and with governance oriented toward verifiable and socially legitimate ecological outcomes (Barragán, 2020; Benalcazar et al., 2024).

3.2 Operational legal model of Galápagos

The regulatory design of Galápagos is grounded in the special regime of constitutional hierarchy established in Article 258 of the Constitution and in the Organic Law of the Special Regime of the Province of Galápagos (LOREG), complemented by the planning instruments of the Galápagos National Park. This

framework establishes clear public purposes, including effective conservation, community well-being, and intergenerational justice, and incorporates friction mechanisms such as effort limits, zoning, biosecurity measures, regulated tourism, sanctions, and mechanisms for substantive participation. These instruments seek to align human activity with ecological carrying capacity and to ensure that the use of natural resources remains within sustainability thresholds (Moya & Muñoz, 2022).

For practical effectiveness, legal mandates must be translated into operational procedures with quantified and verifiable targets. Effort limits require quotas, seasonal restrictions, and permitted gear supported by monitoring and review cycles; zoning demands coherence between terrestrial and marine areas, ecological connectivity, patrol systems, and traceability; biosecurity prioritizes entry controls, early detection, and rapid response; tourism management applies site specific carrying capacities, mandatory itineraries, operational standards, and audited reinvestment; sanctions must ensure proportionality, effective enforcement, confiscation, and environmental remediation; and participation mechanisms must guarantee real decision making influence grounded in local evidence (Rodríguez et al., 2016; Pino & Casanova, 2019).

The connection between design and implementation depends on clear and coordinated institutions, stable multi-annual funding, trained personnel, adequate infrastructure, interoperable information systems, transparency, and accessible environmental justice. Adaptive management reinforces this linkage through public indicators of pressure, state, and response, predefined decision thresholds, and periodic adjustments of quotas, zoning, and biosecurity protocols. Under the principle of *in dubio pro natura*, doubt favours ecological integrity, and restoration is an enforceable obligation in cases of harm, ensuring that normative design yields verifiable and socially legitimate outcomes consistent with *Buen Vivir* and comparative conservation standards (Ochoa, 2024; Díaz, Chiriboga, & Zambrano, 2025).

3.3 Replicable Lessons within leading ecosystem conservation models

Ecosystem conservation has become an essential pillar for ensuring environmental sustainability and biodiversity protection across diverse geographic and regulatory contexts. Globally, various countries have developed legal frameworks and operational instruments that combine zoning, sectoral regulation, access control, and community participation to ensure that conservation objectives translate into concrete and verifiable outcomes. However, the effectiveness of these models depends on institutional coordination, adequate funding, technical capacity, and adaptive monitoring mechanisms. Comparative experiences provide valuable lessons on how to harmonise legal frameworks, operational management, and social participation, offering replicable tools to strengthen conservation at local and regional levels (Villaruel, Rivera-Velasco, & Arandia-Zambrano, 2022). Table 1 below presents an analysis of international ecosystem conservation

models, emphasising their instruments, implementation challenges, and replicable lessons.

Table 1 – Ecosystem conservation models

Country	Legal Basis or Main Framework	Key Instruments	Implementation Challenges	Replicable lessons	Legal sources/Regulation
Ecuador Galapagos Islands	Special constitutional regime Art. 258, LOREG, Galapagos National Park Management Plan, Rights of Nature and Good Living.	Zoning, biosecurity, fisheries regulation, regulated tourism, effort limits, and participation.	Funding and interinstitutional coordination; risk of paper parks if implementation fails.	Regulatory friction combined with adaptive management and meaningful participation.	Constitution of the Republic of Ecuador 2008; LOREG 2015; Galápagos National Park Law.
Russia	Federal Law No. 33 FZ with six categories of protected areas and internal zoning.	Specific prohibitions and use mechanisms; recognition of local and Indigenous rights.	Balancing restrictions and resource use under development pressures.	Combine zoning and local rights to enhance legitimacy and compliance.	Federal Law No. 33 FZ; Protected Areas Law of Russia.
China	National park system reform; systemic design with forthcoming Protected Areas Law.	Zoning as a central tool; multilevel governance; multiagency coordination.	Full regulatory articulation and operational deployment.	Systemic design and multilevel coordination for coherence and effectiveness.	National Parks Law of China in reform process; Protected Areas Law in reform process
Indonesia	Domestic framework plus CITES addressing wildlife trafficking and coastal and marine pressures.	Interinstitutional coordination, regulatory clarity, trade control.	Strengthening sustained coordination and clarity of competencies.	Integrate international commitments with domestic frameworks and agencies.	Biodiversity Conservation Law; Indonesia Protected Areas Law.
Vietnam	Operational forest management based on ranger stations and patrol systems.	Planning adapted to altitude, patrol speed, and patrol hours.	Fine-tuning to territorial conditions and local capacities.	Patrol metrics and territorial adaptation to improve effectiveness.	Forest Management Law of Vietnam; Biodiversity Conservation Law.
India	Biodiversity regime for maritime zones and	Regulatory and operational adjustments for	Effective enforcement in marine protected areas and	Harmonise marine frameworks with enforcement capacity.	Biodiversity Conservation Law of India; Marine

Country	Legal Basis or Main Framework	Key Instruments	Implementation Challenges	Replicable lessons	Legal sources/ Regulation
	marine protected areas.	marine enforcement.	regulatory coherence.		Protected Areas Act.
Seychelles	Insular framework with sectoral overlap.	Need for simplification and institutional clarity.	Regulatory fragmentation and overlapping mandates.	Regulatory simplification and clarity of mandates.	Seychelles Protected Areas Act.
England	Marine regime within the European and national framework.	Coherence among objectives, zoning, and compliance standards.	Overlapping instruments and coherence gaps.	Align objectives with zoning and verifiable standards.	Wildlife Protection Act of England; United Kingdom Marine Protected Areas Act.
Colombia	Normative and institutional system with constitutional and international anchoring.	Articulation of environmental rights and principles for governance.	Maintaining capacity and coordination for implementation.	Constitutional anchoring strengthens legitimacy and compliance	Constitution of 1991; Colombia Protected Areas Law
Brasil	Vitória Trindade chain: protection alternatives for oceanic archipelagos.	Harmonisation of categories and jurisdictions; proposal for legal personality of protected áreas.	Coordination across levels of government and productive sectors.	Multijurisdictional harmonisation and innovative legal tools.	Brazil Protected Areas Law; Oceanic Archipelagos Management Law.

The special regime of Galápagos articulates constitutional mandates concerning the province and the Rights of Nature with the Organic Law of the Special Regime of the Province of Galápagos and the 2014 Management Plan, which integrates terrestrial and marine management through zoning, biosecurity, and limits on fishing and tourism effort. This framework establishes a Governing Council with planning, land use regulation, and interinstitutional coordination powers, and requires monitoring through indicators and protocols to sustain adaptive management and prevent gaps between regulation and implementation. Taken together, institutional design, zoning, and control mechanisms transform the conservation mandate into verifiable and socially legitimate outcomes in a context of high bioinvasion and tourism pressure (Constitution of the Republic of Ecuador, 2008; Organic Law of the Special Regime of the Province of Galápagos, 2014).

Russia consolidates a system of specially protected territories through Federal Law 33 FZ, which establishes categories and internal zoning to regulate uses and prohibitions. Official doctrine and compilations highlight its broad coverage and

implementation challenges, including balancing conservation and resource use (Russian Federation, 1995).

China formalised in 2021 its first batch of five national parks within a multilevel reform aimed at regulatory coherence and integrated governance, with recent progress in registering natural asset rights within these parks, strengthening legal certainty and adaptive management (State Council of the People's Republic of China, 2021; State Council Information Office, 2025).

Indonesia bases conservation on Law No. 5 of 1990 on Living Natural Resources and Their Ecosystems, which serves as the cornerstone for wildlife trade control measures and coordination with international commitments. However, the literature emphasises the need for sustained enforcement and clear allocation of competencies in addressing illegal trafficking (Republic of Indonesia, 1990). In Vietnam, the 2017 Forestry Law strengthens the legal foundation for management and enforcement, while the adoption of the SMART system enhances patrol operations, data collection, and operational feedback, improving adaptive decision making in protected areas (National Assembly of Vietnam, 2017).

In India, the Wildlife Protection Act of 1972 provides the conservation framework, and official reports indicate an extensive network of marine protected areas, with ongoing challenges in coastal enforcement and operational coherence across administrative levels (Government of India, 1972). Seychelles has institutionalised its Marine Spatial Plan through zoning and management plans that seek to align conservation objectives with blue economy development, legally committing nearly 30 per cent of its jurisdictional waters (Government of Seychelles, 2025). In England, the Marine and Coastal Access Act of 2009 enables the establishment of Marine Conservation Zones and related byelaws, supported by technical guidance and scientific advisory protocols that promote verifiable compliance standards (UK Parliament, 2009; Joint Nature Conservation Committee, 2019).

Colombia anchors its environmental governance in Law 99 of 1993, which created the National Environmental System, and in Decree 2372 of 2010, which organises the National System of Protected Areas and its management categories, strengthening interinstitutional coordination and the legitimacy of conservation decisions (Congress of the Republic of Colombia, 1993; Presidency of the Republic of Colombia, 2010). Brazil structures its system under Law 9.985 of 2000 and Decree 4.340 of 2002, which establishes the National System of Conservation Units and its internal zoning. In the oceanic domain, the expansion of protected areas and regulatory alternatives for the Vitória Trindade chain demonstrates both progress in coverage and ongoing challenges in governance and ecological connectivity (Federative Republic of Brazil, 2000, 2002; International Union for Conservation of Nature, 2018).

3.3 Performance evaluation of the Galápagos Islands conservation model

The performance evaluation of the Galápagos model integrates three complementary layers of planning and management. The 2014 Management Plan establishes the conceptual framework, zoning scheme, and monitoring and evaluation system for conservation and sustainable use of the archipelago. In 2015, the Management Model operationalised these guidelines through the definition of programs and projects and the implementation of an external evaluation system that ensures indicator traceability. The Galápagos 2030 Plan incorporates a transparency and openness approach, introducing a public monitoring and indicator classification system to strengthen accountability (see Table 2). This structure ensures coherence among conservation objectives, public use, and the sustainable development of the archipelago.

Table 2 – Performance evaluation of the Galápagos model in accordance with the 2014 to 2020 protected areas management plans

Dimension	Current Performance / Achievements (based on 2014 Plan and 2015 to 2020 period)	Opportunities for Improvement (Key Actions)	Suggested KPI (definition · unit · frequency · baseline / 2030 target)
Governance	Programmatic and project framework defined in the 2015 Management Model, including programs, projects, and interinstitutional coordination. The 2014 Plan establishes zoning and a monitoring and evaluation chapter with indicators. The 2030 Plan aligns axes and objectives with the SDGs and participation mechanisms.	<ul style="list-style-type: none"> • Implement a public dashboard tracking progress by program and project • Formalise coordination spaces such as advisory councils and working groups • Digitise permits and administrative procedures 	% projects on track = (green projects or ≥80% completion / total projects) × 100. Quarterly · Baseline: 2025 · Target 2030: ≥90% % procedures digitised = (fully online procedures / total procedures) × 100. Semiannual · Baseline: 2025 · Target 2030: ≥95%
Biodiversity and Conservation	High pressure from introduced species (1,579 recorded by 2017; +156 between 2008 and 2017) and ambitious conservation targets such as 95% of species in optimal status as an aspirational benchmark.	<ul style="list-style-type: none"> • Strengthen biosecurity at ports and airports • Prioritise eradication and control in critical islands and sites • Implement systematic ecological monitoring 	Number of invasive species eradicated or controlled per year · count · index 0–1 · annual Baseline: establish in 2025 · Target 2030: ≥0.8
Tourism and Public Use	Historical tourism growth of +8% annually since 1979;	<ul style="list-style-type: none"> • Diversify tourism supply, increasing land- 	% sites complying with acceptable visitor capacity =

Dimension	Current Performance / Achievements (based on 2014 Plan and 2015 to 2020 period)	Opportunities for Improvement (Key Actions)	Suggested KPI (definition · unit · frequency · baseline / 2030 target)
	275,817 visitors in 2018 and 271,238 in 2019 (-1.7%). SIMAVIS functions as an acceptable visitor carrying capacity management tool.	based and community tourism value <ul style="list-style-type: none"> • Decentralise visitor flows and reinforce control in sensitive sites • Professionalise service quality 	(sites meeting capacity / monitored sites) × 100 Quarterly · Baseline: 2025 · Target 2030: ≥95% Average expenditure per visitor (national/international) = USD per visit Annual · Baseline 2014: USD 694.75 / USD 2,296 Target 2030: +15% for both groups and reduced gap between them
Local Economy	High dependence on tourism: tourism-related activities represent 64% of provincial gross value added; public administration accounts for 9.4%.	<ul style="list-style-type: none"> • Promote local value chains such as agriculture, sustainable fisheries, and manufacturing • Support entrepreneurship, innovation, and local public procurement 	% non-tourism GVA = share of gross value added not derived from tourism Annual · Baseline: 36% · Target 2030: ≥45% Diversification index (inverse HHI) Target 2030: +20%
Energy	Household electricity coverage 99.7%; only 14% renewable energy; electricity subsidy 73%; annual energy subsidy expenditure approximately USD 53 million; demand grows 6.6% annually.	<ul style="list-style-type: none"> • Increase renewable energy through solar diesel hybrid systems and storage • Improve energy efficiency in urban islands • Decarbonise maritime and land transport 	% renewable energy = (renewable MWh / total MWh) × 100 Monthly · Baseline: 14% (2019) · Target 2030: ≥50% Avoided tCO ₂ compared to diesel = tons of CO ₂ not emitted due to renewable use Target 2030: ≥35,000 tCO ₂ per year
Mobility	4,536 land vehicles in 2019; 49% without entry permit; 355,000 air passengers in 2019; household internet coverage 41.8%; approximately 60% smartphone usage, indicating a digital divide.	<ul style="list-style-type: none"> • Regularise and renew vehicle fleet and discourage unauthorised vehicles • Promote shared electric mobility and improve public and maritime transport • Implement fibre optic plan and digital literacy programs 	% trips using sustainable mobility (public transport, bicycle, walking, shared electric) Annual · Baseline: 2025 · Target 2030: ≥40% % vehicles regularised = (vehicles with permit / total vehicles) × 100 Semiannual · Baseline: 51% (2019) · Target 2030: ≥90%
Community (Education and Health)	Basic coverage guaranteed, but frequent medical transfers; limited local higher education; 2030 Plan prioritises quality of life and empowered citizenship.	<ul style="list-style-type: none"> • Train technical talent on islands in energy, tourism, biosecurity, and data • Strengthen telemedicine and referral networks • Promote affordable housing near essential services 	Doctors per 10,000 inhabitants · ratio · annual · target ≥ mainland Ecuador % higher education degrees completed on islands Target 2030: ≥25%
Habitat and Basic Services	81.4% of population in urban areas; 3.28% of the territory occupied	<ul style="list-style-type: none"> • Accelerate safe drinking water and sanitation systems 	% households with safe drinking water Target 2030: ≥95%

Dimension	Current Performance / Achievements (based on 2014 Plan and 2015 to 2020 period)	Opportunities for Improvement (Key Actions)	Suggested KPI (definition · unit · frequency · baseline / 2030 target)
	by settlements; 51.3% unsatisfied basic needs; waste generation 0.78 kg per resident per day and 0.85 kg per visitor per day; dispersed urban expansion increases cost and risk.	adapted to volcanic terrain. <ul style="list-style-type: none"> • Implement integrated waste management, including reduction, recycling, and recovery. • Promote compact urban planning and affordable housing near employment. 	Waste management rate and generation reduction Baseline 2019: 0.78 kg resident / 0.85 kg visitor per day Target 2030: ≥85% properly managed and –20% generation reduction (approximately 0.62 / 0.68 kg per day)
Finance and Institutional Sustainability	High dependence on tourism revenue and public transfers as described in the 2014 and 2030 Plans.	<ul style="list-style-type: none"> • Diversify funding sources, including environmental service fees, international cooperation, debt for nature swaps, and conservation payments • Improve self-management and cost recovery 	$\% \text{ non-tourism own revenues} = (\text{non-tourism revenues} / \text{total revenues}) \times 100$ Annual · Baseline: 2024 · Target 2030: ≥30% $\text{Revenue elasticity relative to arrivals} = (\% \text{ revenue change} / \% \text{ visitor change})$ Annual · Target 2030: <1.0
Monitoring and Evaluation	The 2014 Plan defines a management and impact indicator system with periodic reviews; the 2030 Plan emphasises transparency and participation.	<ul style="list-style-type: none"> • Publish quarterly reports and open datasets • Integrate observatories for tourism, energy, and biosecurity • Promote citizen audits 	$\% \text{ indicators updated within 12 months}$ Quarterly · Target 2030: ≥95%

The zoning scheme established in the 2014 Management Plan classifies areas into protection, conservation, and controlled use zones, managing natural resources according to their ecological fragility. Acceptable visitor carrying capacity, measured through SIMAVIS, regulates tourist flows to prevent ecological overload. Compliance with these guidelines serves as an indicator of zoning effectiveness and ensures conservation without compromising tourism development. In addition, the Plan’s monitoring and evaluation system compiles annual and quarterly indicators, externally assessed, enabling management plans to be adjusted based on empirical data and promoting efficient adaptive management.

The 2015 Management Model strengthens the implementation of the 2014 Management Plan by establishing a clear structure of responsibilities, timelines, and continuous evaluation. Each project includes a defined baseline, allowing progress to be measured against established objectives. External evaluations conducted by independent assessors ensure that projects are implemented according to defined standards and that expected outcomes are achieved. This approach guarantees transparency and accountability, which are fundamental to the effective implementation of the model and the continuous improvement of the

Archipelago's management system (Ministry of the Environment of Ecuador, 2014).

The Galápagos 2030 Plan promotes transparency by publishing monitoring results in real time, allowing managers and citizens to track compliance with indicators. The classification of results as achieved, below expectations, or lacking information facilitates decision-making and the identification of areas for improvement. This openness enhances accountability and encourages community participation in conservation and development processes within the archipelago. By integrating technology and access to information, the 2030 Plan strengthens the adaptive capacity of the management model, closing the cycle of planning, implementation, evaluation, and adjustment (Ministry of the Environment of Ecuador, 2019).

4 DISCUSSION

Comparative evidence shows that effective conservation frameworks combine graded zoning, multilevel governance with defined competencies, and participation mechanisms with real decision-making influence. These systems are reinforced by regulatory friction tools such as controls and sanctions that slow high-impact activities and secure minimum ecological safeguards. Their success depends on converting principles into verifiable compliance standards and adaptive management cycles supported by public data and stable financing (UNESCO, 1972; UNESCO, 2025; Rodríguez et al., 2016; Massé, 2019; Villarroel, Rivera-Velasco, & Arandia-Zambrano, 2022).

European and island experiences demonstrate that conservation is most effective when legal design is aligned with technical capacity and operational metrics, including marine byelaws, spatial planning targets, and monitoring systems that link evidence to management adjustments. Conversely, misalignment between objectives, zoning, and enforcement standards increases regulatory inefficiency (UK Parliament, 2009; Joint Nature Conservation Committee, 2019; Government of Seychelles, 2025; Puritz and Hill, 2020; Dardi and Shanthakumar, 2023).

Asia, Russia, China, and Indonesia illustrate complementary strategies such as categorical zoning with recognition of local rights, systemic national park reforms, and alignment of international commitments with domestic enforcement. Vietnam and India highlight the importance of patrol metrics and marine enforcement coherence. In Latin America, Colombia's constitutional anchoring and Brazil's innovative legal approaches, including proposals for the legal personality of protected areas, reinforce legitimacy and governance capacity.

Within this comparative landscape, Galápagos functions as a legal ecological laboratory. Its constitutional special regime, implemented through LOREG and successive planning instruments, integrates zoning, biosecurity, fisheries and tourism regulation, and participatory governance under the framework of Buen Vivir and the Rights of Nature. The 2014 Plan, the 2015 Management Model, and

the 2030 Plan together close the cycle of planning, implementation, evaluation, and transparency, positioning Galápagos as a regional benchmark of verifiable conservation (Constitution of the Republic of Ecuador, 2008; LOREG, 2015; Ministry of the Environment of Ecuador, 2014; Ministry of the Environment of Ecuador, 2019; Barahona & Añazco, 2020; Garate et al., 2024).

However, structural tensions remain, including tourism dependence, invasive species pressure, and enforcement gaps. Strengthening *in dubio pro natura*, restoration obligations, and internormative coherence is essential to prevent sectoral permits from undermining ecological thresholds. Converting indicators into binding standards with precautionary triggers, ensuring open data and interoperable systems, and consolidating financial and institutional innovations such as multi-year trust funds and mandatory traceability would enhance deterrence and sustainability. The long-term projection of Galápagos as a replicable model depends on embedding operational standards into binding law and translating the Rights of Nature into tangible ecological outcomes (Rodríguez et al., 2016; Massé, 2019; Pino and Casanova, 2019; Sandoval, Galarraga, & Galarraga, 2021; Barragán, 2020; Benalcázar et al., 2024; Ochoa, 2024; Díaz, Chiriboga, & Zambrano, 2025; UK Parliament, 2009; Joint Nature Conservation Committee, 2019; National Assembly of Vietnam, 2017).

5 CONCLUSION

Effective conservation is not achieved solely through the designation of protected areas, but through a regulatory and institutional framework that integrates zoning with clear effort limits, multilevel governance with defined competencies, and enforcement mechanisms grounded in precautionary criteria and adaptive management. Only the coherent integration of these elements ensures tangible and socially legitimate outcomes.

The Galápagos special regime represents an advanced institutional architecture in the regional context by combining the Constitution, LOREG, and successive management plans (2014, 2015, and 2030). However, its effectiveness faces structural vulnerabilities, including high dependence on tourism, increasing pressure from invasive species, asymmetries in coastal and marine enforcement, and certain regulatory inconsistencies. Addressing these gaps requires strengthening legal enforcement, ensuring integration between terrestrial and marine management, and consolidating stable technical and financial capacities.

Comparative analysis of Russia, China, Indonesia, Vietnam, India, Seychelles, the United Kingdom, Colombia, and Brazil reveals replicable patterns, including internal zoning with recognition of local rights, systemic frameworks coordinated across agencies, mandatory operational metrics, marine spatial planning with verifiable standards, and constitutional anchoring that reinforces the legitimacy of conservation. These experiences provide valuable inputs for refining the Galápagos model and strengthening its adaptive governance.

Consolidating the insular model requires transforming indicators into legally enforceable standards under precautionary criteria, ensuring externally audited open data, establishing traceability in fisheries, tourism, and biosecurity, conditioning licenses on environmental performance, creating a multi-year trust fund supported by national and international contributions, and advancing institutional innovations such as legal recognition of protected areas and formal registration of natural assets. These measures would strengthen ecological protection, secure regulatory coherence, and enhance the long term institutional resilience of the archipelago.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest. The funders had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

DISCLOSURE OF ARTIFICIAL INTELLIGENCE ASSISTANCE

The authors acknowledge the use of artificial intelligence tools in the preparation of this manuscript. Specifically, ChatGPT by OpenAI was utilised to support linguistic refinement and translation. All AI-assisted content was carefully reviewed, edited, and validated by the authors to ensure scholarly integrity, originality, and compliance with ethical standards. The authors affirm full responsibility for the content of the manuscript, including any material generated or supported by artificial intelligence.



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Analysis of Environmental Aspects and Minimisation of the Negative Impact of Adhesive Bonding using Quality Management Tools

DOI: 10.12776/qip.v30i1.2303

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Received: 27-11-2025 Accepted: 09-04-2026 Published: 30-04-2026

ABSTRACT

Purpose: This study aims to investigate the combined application of 5 Why and E-FMEA for evaluating of gluing technology, its quality and waste management.

Methodology/Approach: The research adopted a technical paper. The method of analysing the basic stages of gluing machine parts. Negative impact on the environment is described using algorithms, the Ishikawa diagram, 5 Whys, and 5W2H implemented from the area of quality management.

Findings: The study revealed significant influences and analyses of errors during the manufacturing, minimising of hazardous waste from gluing. The study revealed, based on an employee survey, the impacts and analysis of errors during production, the minimisation of hazardous waste from gluing, and pointed out the effectiveness of teamwork.

Research Limitation/Implication: Focusing on the production with material gluing may not fully represent the environmental impact of production on environment.

Originality/Value of paper: This paper contributes to the limited literature using in the area of influence of gluing technology on the environment.

Category: Technical paper

Keywords: adhesive bonding; environmental Ishikawa diagram; environmental 5 Whys; 5W2H; waste management

Research Areas: Quality Engineering

1 INTRODUCTION

Bonding is still one of the attractive and necessary techniques for joining parts together. It requires the use of an appropriate preparation procedure and meeting specific conditions during the application of the adhesive layer and its curing, but with the current state of technology and the advancement of manufacturing systems, this is not a major problem. Many companies in the world produce adhesives. The adhesive production sector is growing due to the very good properties of the bonded products, high efficiency of the assembly and sealing process. Adhesives are also used as intermediate products in the production of labels, laminates, paper, cardboard and others (Crisostomo, 2020). In the work (Watcharakitti et al., 2023), it is stated that the global market for adhesives and sealants is growing rapidly and is expected to be worth about USD 85.8 billion by 2026. Such dynamic development allows us to assume that bonding technology will be relevant and used for a long time. However, in addition to the undoubted advantages of such connections and their use in many industries, environmental issues should be considered (Cavalanti et al., 2021). They are important due to the variety and number of chemical substances used in gluing and the regulations and directives regulating, among others, hazardous waste issues (Rodriguez et al., 2024). Due to the fact that many activities, both preparatory and related to the creation of an adhesive joint, require the use of preparations that are not always neutral to health and the environment, it is necessary to analyse and search for easy ways to verify the environmental safety of this technology (Montalvo-Romero et al., 2022; Packham, 2009; Badida et al., 2022; Chirdon, 2015).

Methods of estimating environmental impact are a fundamental tool in environmental management, planning and sustainability assessment of projects, technologies or products. These methods are used to quantify and analyse the impacts of human activity on the environment from air, water, soil pollution to resource consumption and climate change. Also, these methods can be used in the adhesive production section.

The main methods for estimating environmental impact include LCA – Life Cycle Assessment, EIA – Environmental Impact Assessment, CF – Carbon Footprint, Ecological Footprint, MFA – Material Flow Analysis, ERA – Environmental Risk Assessment (Tolls et al., 2016; Yang & Rosentrater, 2020; Soos, 2022; Minliang & Rosentrater, 2015).

2 MATERIALS AND METHODS

2.1 Theoretical foundations of analysis

The adhesive bonding process is a complex and multi-stage task, requiring the use of appropriate materials and methods to make a correct connection. In addition to achieving the assumed quality of assembly, environmental issues are of great importance. The adhesive bonding process is divided into three stages (Brezinova,

Guzanova, & Draganovska, 2018; da Silva, Ochsner & Adams, 2011; Ang et al., 2014; Baranska-Miturska et al., 2024):

- I – preparatory – concerning the initial treatment of the surface, selection of glue and the method of its application,
- II – proper – using a primer, preparing the glue mixture, setting the joint, applying glue and gluing the elements together,
- III – final – setting the elements, curing the joint, finishing activities related to, for example, removing excess glue.

Stage I takes into account production requirements, such as joint strength, resistance to external factors, and operating conditions of glued parts. Analysis of the guidelines is the basis for the proper selection of materials (unless imposed by the designer), type of glue and its properties, method of surface pre-treatment (washing, removing old layers or corrosion, removing grease, giving a specific surface roughness, washing again and drying). Sometimes, an additional substance is applied to the prepared surface, increasing the adhesion of the glue to the surface. Correct execution of these activities increases the durability of the joint, reduces the risk of defects and regluing the same elements, and due to environmental protection, contributes to material losses, excessive water consumption for washing the surface, and electricity for heating and drying the parts (Marques et al., 2020).

Stage II is crucial due to the execution of activities aimed directly at connecting the elements. It is carried out as part of the sequentially performed activities, the consequence of which is obtaining a connection of a specified quality. It may start with the application of a primer, i.e. an additional substance improving the adhesion conditions. If it is not needed, stage II begins with the proper preparation of the glue – squeezing, if it is single-component or mixing in the right proportions - if two-component. Measuring and mixing the glue may require the use of additional equipment in the form of containers and mixers. Then, the glue is applied to the surface manually using applicators, spatulas, brushes or mechanically using automatic dispensers with special nozzles (Packham, 2009; Dilger & Frauenhofer, 2017; Krishnasamy et al., 2024; Zhang et al., 2020).

After these activities, stage III begins, related to the determination and hardening of the joint. The glued elements are pressed, if necessary, their position relative to each other is determined using additional clamps, grips or handles, for the time necessary for the glue to harden and to obtain a permanent connection with the assumed properties. Sometimes, the fixing and hardening operation is performed by heating the glued elements. The conditions and time of hardening should be selected taking into account the technical specifications of the glue. After obtaining a joint with the desired properties, the clamps are removed, and if necessary, the joint is levelled, e.g. with files, sandpaper or mechanically, e.g. using hand milling machines (Borges et al., 2023).

2.2 Case description

In the analysed case, gluing at the plant is carried out according to the algorithm given below in three stages. Customers most often order elements made of steel or aluminium alloys, and the plant selects the gluing technology with regard to the strength, operational, aesthetic and cost requirements defined by the ordering party. The plant has various types of adhesives, and if they are not available, adhesives are ordered on an ongoing basis. The same applies to other chemical substances and equipment. For the specific shape of the product, appropriate clamps are designed using standard and readily available elements on the market. In rare cases, there is a need to design special devices or holders. The plant has a prototyping shop, galvanizing shop and heat treatment department, which are adapted to the assembly needs. Various problems were identified in the plant, including waste and hazardous waste, water and electricity consumption. Employees also reported other problems related to the use of various substances, such as health problems and difficult working conditions. To solve these problems, and in particular to identify the types and scale of impact and significance, methods and approaches known from quality management were proposed.

3 ANALYTICAL METHODS AND RESULTS

There are many well-known and widespread methods of managing the quality of products or processes. They are usually not very technically complicated, but they require knowledge that can be successfully gathered, especially in production conditions, where the course of activities and resources are known.

3.1 Adhesive bonding process algorithm

In the context of analysing the sequence of actions performed and assigning decisions and their effects in descriptions and procedures concerning quality, algorithms are used. An algorithm is a simple drawing; its execution allows for visualisation of an ordered sequence of actions. The algorithm was used in the described case to identify the actions necessary to perform in the gluing operation. Known symbols were used to mark the beginning and end of the process, individual stages, emerging documentation and decisions. For the analysed process and the three stages listed earlier, the algorithms shown in the Figure 1 were developed.

In the context of environmental analysis, it does not yet provide direct information on the relationship with the environment, but it serves to organise knowledge about the process and can be used to further identify the impact on this environment. In the case studied, specific means of production, i.e. equipment and substances, were assigned to each stage. Examples of these are shown in Figure 2, Figure 3 and Figure 4.

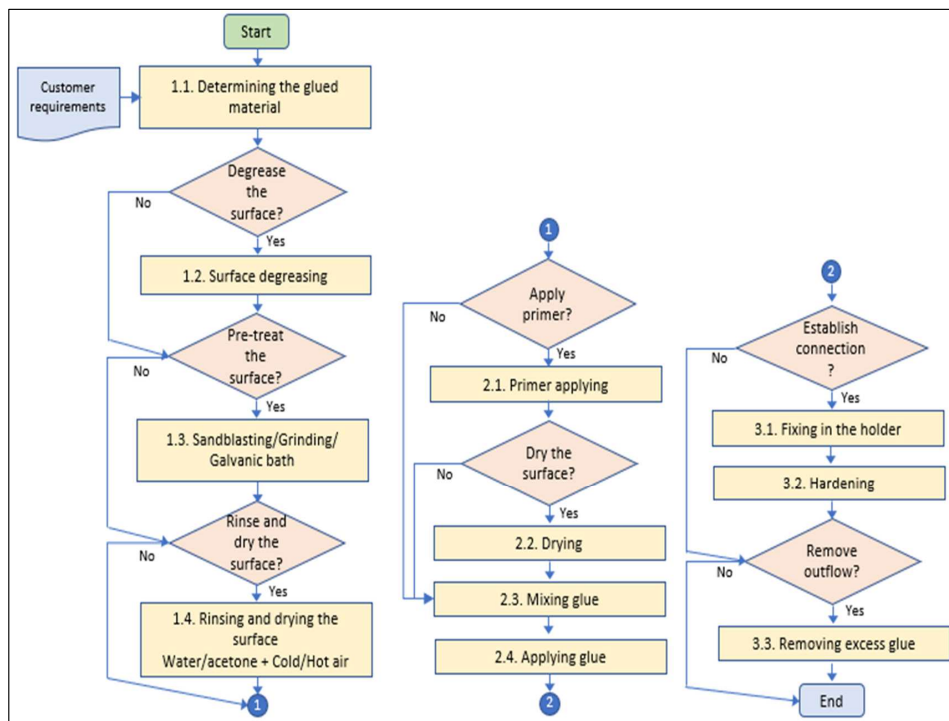


Figure 1 – Algorithms of procedure during gluing: a) stage I – preparatory, b) stage II – gluing, c) stage III – finishing the connection

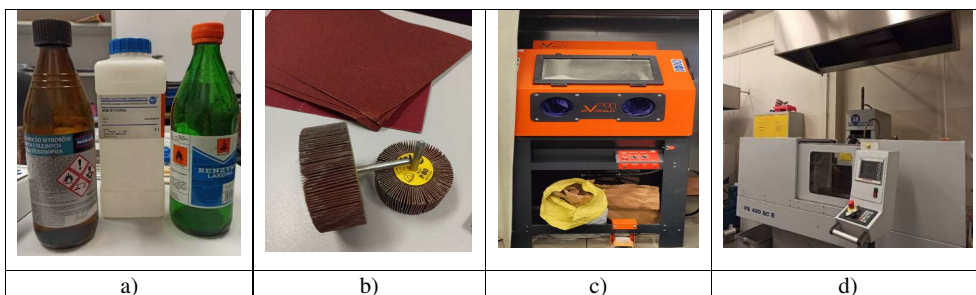


Figure 2 – Examples of equipment and substances characteristic of stage I – preparatory: a) degreasers, b) abrasive tools, c) sandblaster, d) grinder



Figure 3 – Examples of substances and necessary equipment for gluing (stage II): a) primers, b) adhesives for mixing, c) adhesives in tubes, d) brushes, putty knives, tips for glue application, e) devices for squeezing two-component adhesives

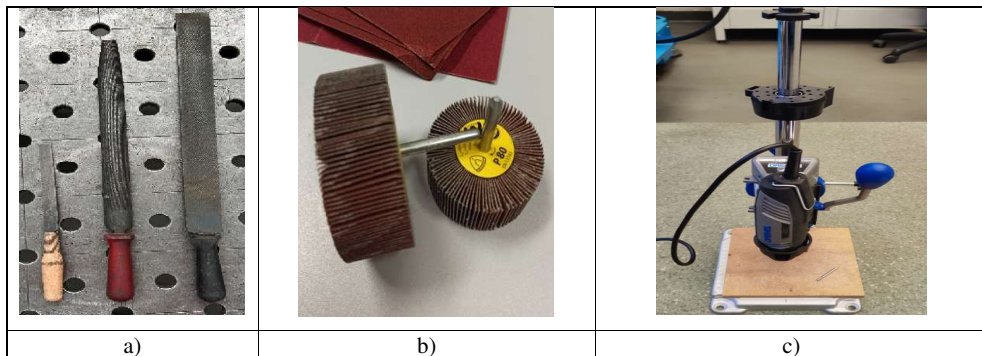


Figure 4 – Examples of production means for carrying out the third – final stage: a) metal files, b) paper grinding wheels, c) hand milling machine

Such systematisation enabled logical and comprehensive identification and assessment of environmental aspects at a later stage of the analysis.

3.2 Ishikawa diagram

The typical approach to the Ishikawa diagram concerns products or processes from the point of view of the quality of workmanship or the correctness of the process. The diagram is a graphic method that allows for the division of various, sometimes chaotic, information and its systematisation according to the initial hierarchy of importance. Information is arranged and assigned to a specific area of activity (Oakland, Oakland, & Turner, 2021). The typical causes of the occurrence of the effect defined at the beginning of the analysis are presented in the form of a fishbone diagram. The diagram for quality most often includes five components of 5M: Man, Methods, Machinery, Materials, Management (Ciecińska, 2023; Ciecińska, Majka, & Sobotová, 2024). Sometimes the E – Environment area is added in the context of the influence of the environment on the product or process (Ilie & Ciocoiu, 2010) (Table 1). The arrows in the diagram direct the influence: how the listed action affects the defined problem (What effect does it bring?). By expanding a given area of causes, you can enter the answers, “Why?”, “For what reason?” this action contributes to the final effect. This gives you a hint on what to do, what to remove, reduce, increase, or change - so that a given negative effect is limited. The Ishikawa diagram used to analyse the defects of bonded products may look as shown in Figure 5.

Table 1 – Ishikawa diagram 5M+E (Ciecińska, 2023)

Field	Problem
Man	Is the loss of quality due to human error?
Method	What work or production methods were used?
Machine	Maybe the error is generated by a faulty machine?
Materials	Could the problem lie in the material from which the product is made?
Management	Do problems arise as a result of lack of supervision, planning, work organisation, poor motivation and leadership, lack of control, and lack of conceptual, technical, and social skills?
Environment	Is the problem the environment of the production station, working conditions, or other people?

A modification of the Ishikawa diagram was proposed and its application for the analysis of the impact of the tested technology on the natural environment. Areas typical of quality were replaced with negative impacts on environmental components, which may be air, water, soil, waste load, demand for raw materials, and other factors burdensome to people (Table 2). Then, for the analysed gluing, a diagram was developed, shown in Figure 6.

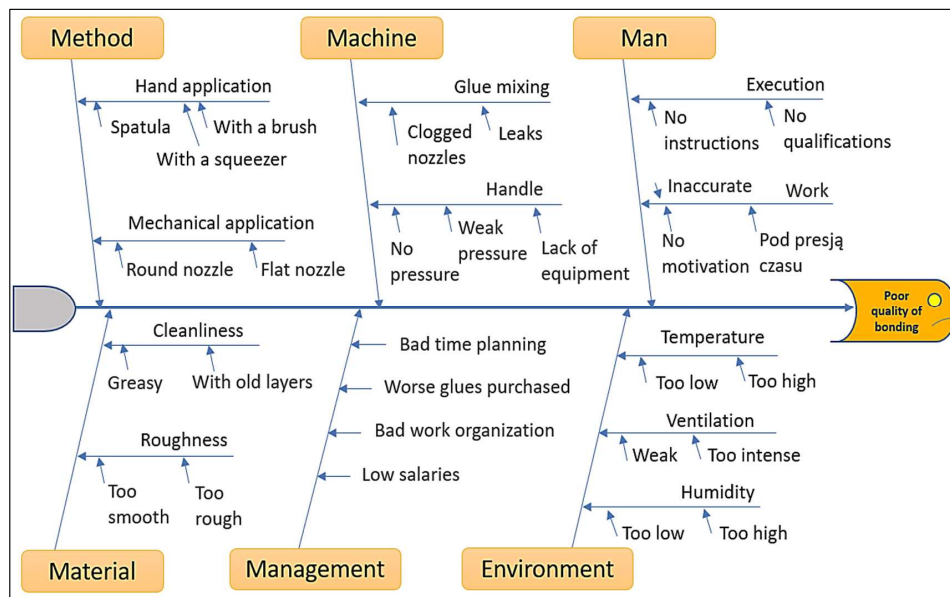


Figure 5 – Ishikawa diagram for bonding quality

Table 2 – Modified Ishikawa influence areas for environmental impact analysis

Field	Problem
Atmosphere	What type of air emissions can cause deterioration of air quality?
Water	How can technology contaminate water intakes?
Soil	How can technology affect soil pollution?
Waste	Why does the problem of waste accumulation arise?
Raw materials/ Energy	Does technology require the use of materials? For what reason? Why is it necessary to use energy? What type or origin?
Nuisance to humans	What poses a threat or what worsens the quality of life of people in the vicinity of the plant or workplace?

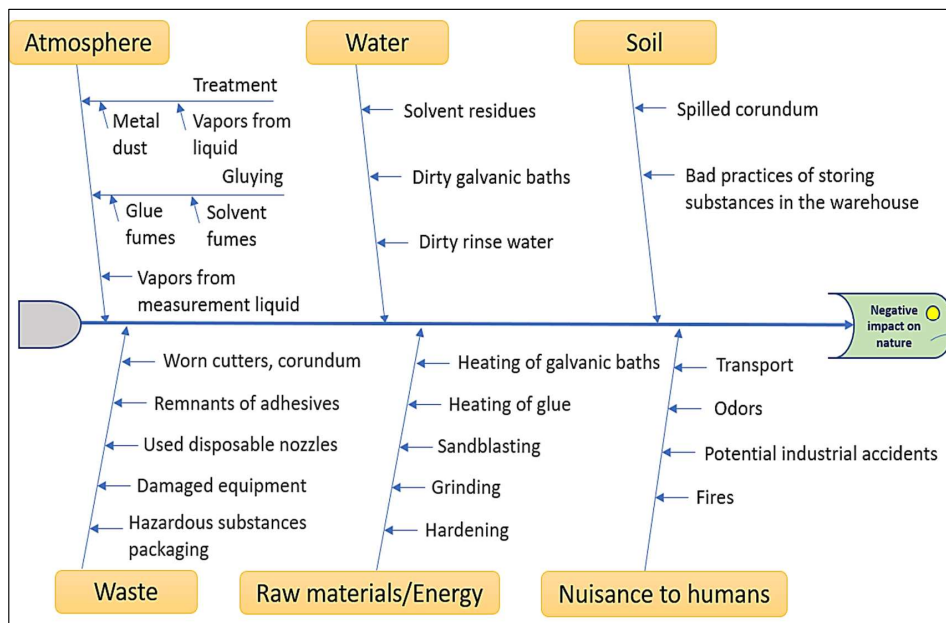


Figure 6 – Ishikawa diagram for assessing the environmental impact of adhesive bonding

The proposed solution can be modified and expanded in subsequent steps, and a given area can become the “head” of the diagram. Additionally, another approach to areas known for quality was proposed, so that they could be related not to the product but to the natural environment. For known 5 M+E areas, their meaning was changed, as shown in Table 3. Using the second modified diagram, the problem of potential industrial failures with environmental effects was analysed concerning the carried-out assembly, Figure 7.

Table 3 – Problem analysis in 5M+E Ishikawa diagram modified for environmental impact

Field	Problem
Man	What human activities negatively impact the natural environment?
Method	How do the methods used affect the demand for raw materials or generate other environmental burdens?
Machine	Is the environmental problem generated by faulty machinery?
Materials	Could the problem lie in the material from which the product is made?
Management	Do problems arise as a result of lack of supervision, planning, work organisation, poor motivation and leadership, lack of control, and lack of conceptual, technical, and social skills?
Environment	Is the problem the environment of the production station, working conditions, or the behaviour of other people?

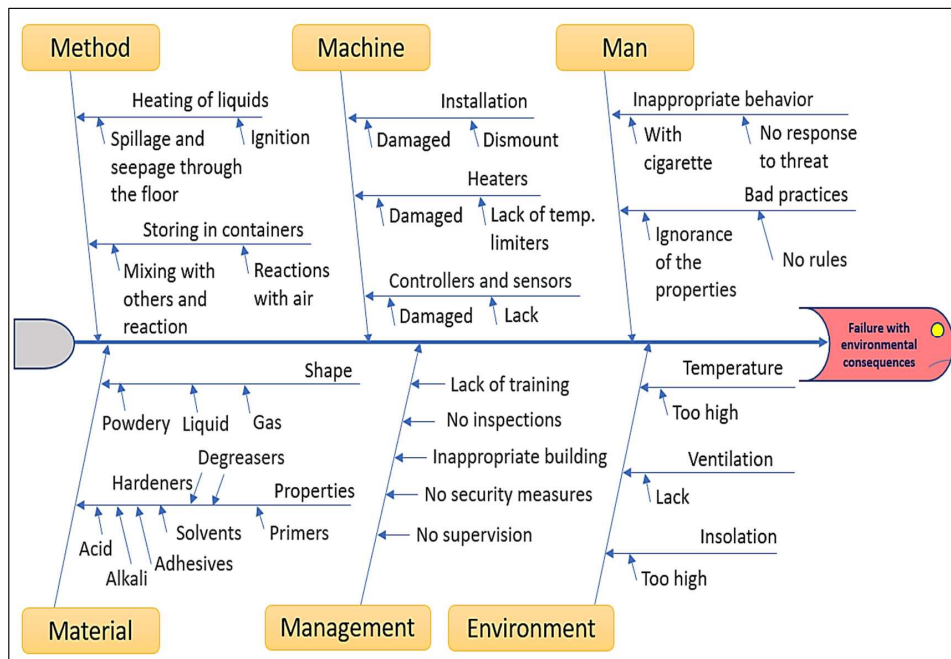


Figure 7 – Ishikawa diagram used to identify potential failure modes due to environmental effects during bonding

In the above example, there was an opportunity to use areas known for quality, while the purpose of the analysis was defined in the context of environmental management.

4 RESEARCH ON AWARENESS AND KNOWLEDGE – ENVIRONMENTAL SURVEY

A natural need in enterprise management, also in the context of environmental problems, is to learn about awareness and state of knowledge among employees at various levels. This is important for determining the scope and difficulty of actions that need to be taken for effective management. A simple method, often used for various marketing or pro-quality studies, is a survey. A survey is a technique using a questionnaire, a specific form of interview used to collect a large amount of information on a given phenomenon, using little effort and resources. The survey questionnaire may contain open questions, allowing the respondent to enter their own answer, semi-open questions – which have proposed answers, but also allow for entering their own, and closed questions – constituting a set of ready-made answers, from which the respondent selects the one that best fits their assessment of the given situation (Midor & Zarnovsky, 2016; Dacko, 2013).

In the analysed case, an environmental survey was prepared to collect information on environmental awareness in a group of 25 employees on the assembly line. The survey questionnaire is shown in Table 4, and the results obtained in Figure 8.

Table 4 – Employee survey project and obtained responses

Environmental survey			
The survey concerns the opinions of employees on the organisation of space for various substances used during gluing. It aims to learn your opinion on this subject and is completely anonymous. Please mark the selected answer in the YES/NO questions (e.g. x and enter your answer in the dotted lines. Thank you for taking the time to answer.			
Type of position held: <i>assembly line worker</i>			
No.	Question	Answer	Results
1.	Can the work you do be done without chemicals? What substances do you use most often? Please list the 3 most frequently used:	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 0 NO 25 glue, acetone, naphtha, TRI, galvanic bath solutions
2.	Have you read the safety data sheets of the substances you use?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 5 NO 20
3.	Do you follow the guidelines given in the material safety data sheet?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 5 NO 20
4.	Does your workstation have an organized place for these substances?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 7 NO 18
5.	Do you consider the current storage location for these substances safe?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 13 NO 12
6.	Do you know the general rules for waste management?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 23 NO 2
7.	Do you know which substances you use will create hazardous waste?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 8 NO 17
8.	Do you have an organised place for this waste?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 8 NO 17
9.	Is there enough training related to substances and their waste?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 4 NO 21
10.	If the stations are properly organised, are you prepared to comply with the provisions of the substance card?	YES <input type="checkbox"/> NO <input type="checkbox"/>	YES 25 NO 0

The survey shows that employees use various chemical substances (Question 1, 25/25), Figure 8. The busiest stations are those for preparing surfaces before gluing, where preparations for various purposes were mentioned: for removing corrosion, for degreasing, washing, creating an oxide layer, solvents (Q1). However, most employees did not read the material safety data sheets (Q2, 20/25). The same employees admitted that they did not comply with the provisions of these sheets (Q3, 20/25). Employees also admitted that not all stations had a place for such substances (Q4, 18/25), and in the opinion of many, the current place of their storage was not safe (Q5, 12/25). Analysing the answers obtained, one can see a connection between the lack of knowledge of the properties of substances and the rules of handling them (from the material safety data sheet of the chemical preparation) and the characteristics of the waste generated by these substances. If an employee does not know that a given substance exhibits environmentally hazardous characteristics, they are also unable to indicate that any items contaminated with it are also hazardous. The general principles of waste

management were declared by most employees (Q6, 23/25), but only eight respondents were aware that a given waste is hazardous (Q7, 17/25 are not aware of this). Many employees responded that there is no organised place for waste (Q8, 17/25). In turn, the amount of training is sufficient in the opinion of only some employees (Q8, 4/25), although this does not translate into everyday practices (according to Q3, 20/25 do not use or have no knowledge). However, all respondents expressed their willingness to follow good practices in connection with waste, if only the assembly stations are organised in the right way (Q10, 25/25).

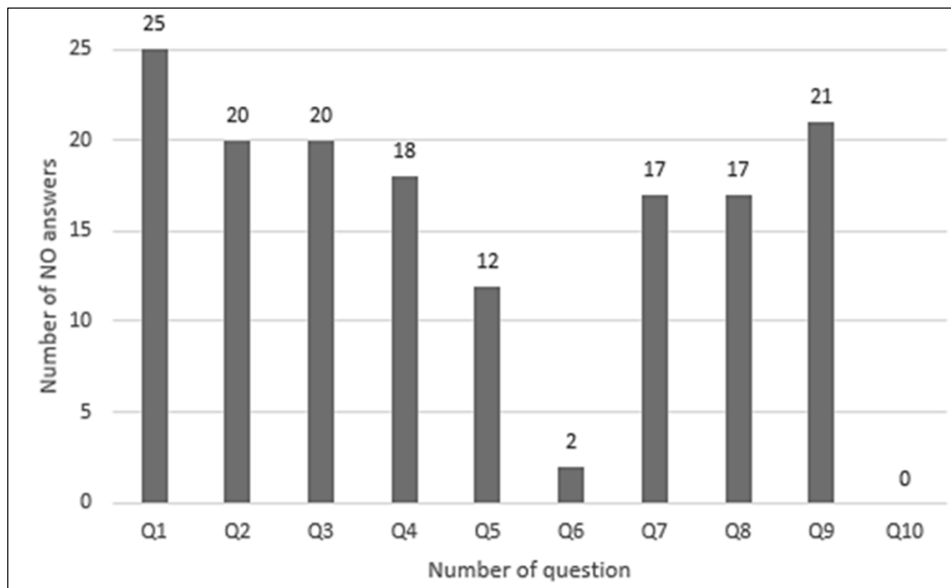


Figure 8 – Summary of the results of the environmental survey, which illustrates the scale of poor environmental practices

The chart shows the scale of negative phenomena in the plant in the context of environmental protection: unawareness, ignorance, bad practices or negative feelings of employees. To improve, it is necessary to make the real conditions be assessed more favourably and the numerical values shown in the chart be lower.

4.1 5 Whys and 5 W2H

The aim of the 5 Whys method is to discover the root cause of the problem by successively asking the question “Why?” – why it is happening as indicated in the previous answer. In this way, it is easier to understand the cause of the problem, and also to define the means to eliminate it. The initial stage is to collect as much knowledge as possible about the problem that has arisen, while each subsequent step increases the probability of discovering the root cause. The diagram for 5 Whys is in the form of a tree, such a graphical representation is easier for logical reasoning (Ciecińska, 2023; Ciecińska, Majka, & Sobotová, 2024). The survey

conducted at the gluing stations shows, among other things, that the problem in the context of environmental impacts is the improper and dangerous storage of chemical substances during assembly, which are particularly abundant in gluing operations (Kovács, Weltsch, & Berczeli, 2024). The cause of this state was determined using 5 Whys, the results of which are shown in Figure 9.

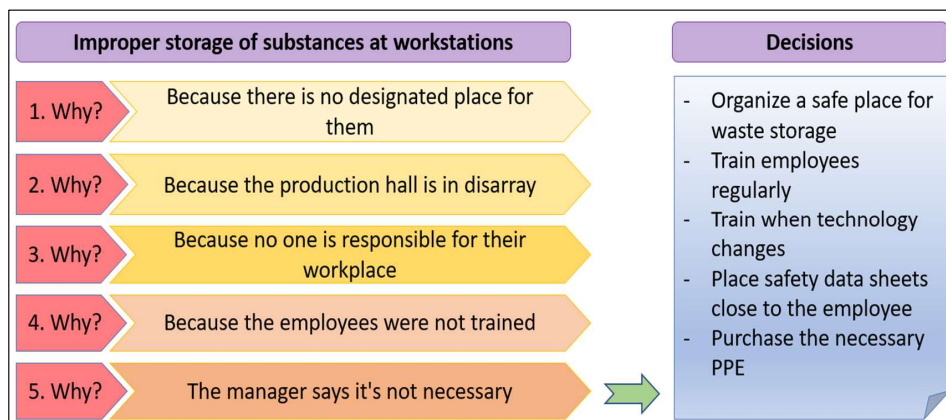


Figure 9 – Finding a solution to the waste problem using the 5 Whys method

A variation of 5 Why is the 5 W2H analysis, in which the questions are defined in a different way. Referring to the impact on the natural environment, the interpretation of the analysis elements given in Table 5 is proposed.

Table 5 – 5W2H for waste environmental burden analysis

Question	Problem
What?	What happened? What is the environmental problem?
Who?	Who reported the problem? Does it directly affect them?
Where?	What area is affected by the harmful impact? Is it large or small?
When?	When was the problem reported? Was it a one-off or recurring situation?
Why?	Why did the problem occur and what effects it might have?
How?	How was the problem assessed? Did the assessment concern measurable parameters, or are other, further studies and measurements needed?
How many?	What is the scale of the problem over a specific time period?

The results of the analysis performed in this way are shown on Figure 10.

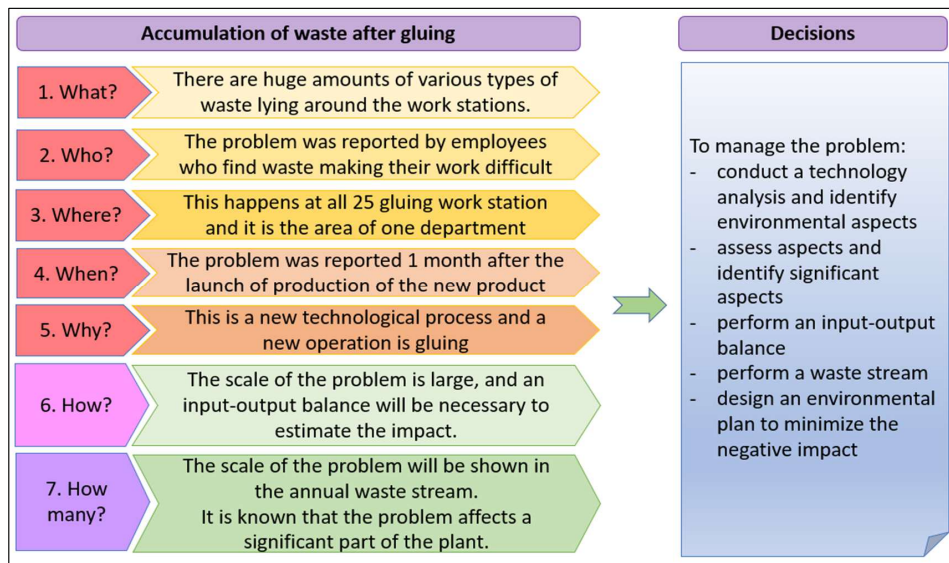


Figure 10 – Result of 5W2H analysis of waste from substances used in adhesive bonding

Due to the findings made during the 5 Why and 5 W2H analysis, a comprehensive identification of environmental aspects was carried out to assess the scale of impact. Although employees reported one problem, it is likely that there will be more environmental impacts and they may be diverse.

4.2 Register of environmental aspects

In the next step, a detailed analysis of the gluing process was performed and factors that could cause a negative environmental effect were identified. Based on this, a register of environmental aspects was created, according to the division into stages shown in the algorithms in Figure 1. The results of aspect identification are given in Table 6 to Table 8.

Table 6 – Register of environmental aspects identified in stage I of adhesive bonding

Register of environmental aspects		
Applying to the station / process: <i>assembly of metal machine parts - preparatory activities before gluing</i>		
No.	Environmental aspect / Activity	Method of impact on the environment
1.1 Determining the glued material /Accepting an order from a customer		
	Removing packaging material from sheet metal, securing products secured for transport	Packaging waste burden: unnecessary paper, cardboard, plastic foil, wooden pallets, metal clamps

Register of environmental aspects		
Applying to the station / process: <i>assembly of metal machine parts - preparatory activities before gluing</i>		
No.	Environmental aspect / Activity	Method of impact on the environment
1.2. Surface degreasing		
	Using a cloth moistened with a degreasing liquid	Hazardous waste load: used cleaning materials
	Ultrasonic bath in solvent	Potential water pollution in the event of pouring used liquid into the sewage system Load of hazardous liquid waste suitable for disposal Load of hazardous waste in the form of empty liquid packaging - metal cans, bottles Electricity demand
1.3. Sandblasting / Grinding / Galvanic bath		
	Manual abrasive processing or using mechanized tools	Waste load from used abrasive tools Abrasive material particle emissions to air Hazard to human health
	Machine abrasive processing	Dust emissions to air Waste burden – spent corundum and potential soil contamination from spent corundum Electricity demand
	Chemical surface treatment	Demand for chemicals Load of liquid hazardous waste in the form of dirty acid, alkali and salt baths Emissions of harmful aerosols into the air and a threat to human health Potential risk of spillage and contamination of soil and groundwater Demand for clean process water and the creation of hazardous waste after rinsing Potential risk of failure with an environmental impact - ignition and fire of liquids, secondary emissions into the air, secondary contamination of water and soil Load of hazardous waste from packaging of chemical reagents (glass bottles, plastic or metal containers)
1.4. Rinsing and drying the surface		
	Cleaning	Demand for demineralized water, depletion of natural resources Demand for chemicals (acetone, naphtha) Load of waste from water packaging Load of hazardous waste from packaging for other liquids
	Drying	Electricity demand in furnaces and heaters Waste from spare parts from devices Waste from control systems (e-waste)

Table 7 – Register of environmental aspects identified in stage II of adhesive bonding

Register of environmental aspects		
Applying to the station / process: <i>assembly of metal machine parts - preparatory activities before gluing</i>		
No.	Environmental aspect / Activity	Method of impact on the environment
2.1. Primer applying		
	Covering the surface with primer	Load of hazardous waste from used workshop application aids (putty knives, brushes), pressurized metal cans, dirty plastic containers, dirty cleaning cloth Load of packaging waste: paper, cardboard, plastic foil Emissions of harmful vapours into the air
2.2. Drying		
	If the layer is to be dry before applying the glue - drying	Electricity demand Hazardous waste load: used cleaning materials
2.3. Mixing glue		
	Dosing resin and hardener	Hazardous waste load in the form of: dirty tubes, applicators, mixers, containers Emissions of harmful substances from adhesives and hardeners into the air Threat of damage to human health Electricity demand during adhesive dissolution
2.4. Applying glue		
	Covering the surface with glue mixture	Hazardous waste load in the form of: dirty spatulas, brushes, applicators, containers Emissions of harmful substances from adhesives and hardeners into the air Threat of damage to human health Electricity demand for mechanical application

Table 8 – Register of environmental aspects identified in stage III of adhesive bonding

Register of environmental aspects		
Applying to the station / process: <i>assembly of metal machine parts - preparatory activities before gluing</i>		
No.	Environmental aspect /Activity	Method of impact on the environment
3.1. Fixing in the holder		
	Bonding using retaining elements	Load of metal waste in the form of destroyed equipment elements (pressure pads, flaps, spacers, etc.)
3.2. Hardening		
	Obtaining a join with specified properties	Energy demand during heat or hot curing Waste load from possibly used heaters or control elements
3.3. Removing excess glue		
	Manual or mechanical finishing of the join	Electricity demand during the use of mechanized tools (milling machines) Load of hazardous waste in the form of hard glue chips Emissions of glue particles into the air Threat to human health resulting from inhalation of particles and dust Load of waste from poorly made products, damaged tools (milling cutters, files)

The comparisons show that many types of impacts are repeated in individual activities performed during gluing. Since they are repeatable, the scale of the negative impact increases, and the impact on human health is also greater, due to more frequent exposure to harmful factors. It can be said that by performing environmental analyses, one can also refer to problems with occupational safety and occupational risk. Looking at this problem more broadly, any action that minimizes the environmental impact will also improve working conditions and reduce the risk of occupational diseases in people.

4.3 Assessment and Register of Significant Aspects

Due to the recommendations resulting from the 5 W2H analysis concerning the need to reliably determine the significance of the environmental impact of the reported problems, an assessment of the identified aspects was carried out and significant aspects were selected. The assessment of aspects was carried out using the FLIPO method, which was analysed in five steps:

- Flow – flow of materials, energy, information – what substances, materials, types of energy or waste are introduced into the manufacturing processes in the plant, how they are processed, what their use is in the context of the flow of products in the process.
- Legislation – what standards, laws, and regulations apply in a given scope in the context of the environment, whether the plant complies with these provisions, whether the requirements are exceeded, how higher environmental protection standards can.
- Impacts – what are the direct and indirect impacts of the activity on the environment, whether these are emissions, pollutants released into water, soil, atmosphere, degradation of ecosystems, consumption of natural resources, especially non-renewable ones, waste generation and impact on human health, then it is possible to qualify the impact according to importance and take appropriate corrective measures.
- Practices – What is done in the plant to protect the environment? The analysis includes production methods, waste management methods, savings e.g. water, energy, emission monitoring, as well as applied improvements and assessment of the effectiveness of these actions.
- Opinions – collection of opinions of employees and external stakeholders: customers, suppliers, local community, non-governmental organizations, etc. Feedback is received on the need, meaning, effectiveness, and efficiency of actions.

The importance of an aspect is determined by adding the partial scores collected in the above five areas. The numerical score is determined according to the principle given in Table 9.

Table 9 – Categories and criteria for assessing environmental aspects

No.	Category	Criteria and number of points		
		1	2	3
1.	Flow	Very important	Important	Normal
2.	Legislation	There is a regulation and it is not fulfilled	There is regulation and there is a risk of exceeding	There is a regulation and it is fulfilled
3.	Impacts	The aspect is dangerous, reacts with the environment, affects human health	The aspect is probably not harmful, but in large quantities it can cause hazards	The aspect is not harmful
4.	Practices	To cease immediately	To change	To check
5.	Opinions	There are complaints about the company's impact on the environment	There is general interest	Lack of interests

The previously identified aspects were assessed by 30 people and the average results obtained are shown in Table 10.

Table 10 – Aspects assessment in adhesive bonding

No.	Field of impact	Environmental aspect	Environmental impact	Category and number of points					Σ
				F	L	I	P	O	
1.	water	water consumption for galvanic baths	consumption of non-renewable resources	3	3	2	1	1	10
2.	soil, water	nuisance leaks of substances from machines and devices	environmental pollution	2	2	1	3	2	10
3.	soil	incorrect securing of hazardous substances	environmental pollution, risk of failure, threat to life	2	3	3	2	3	13
4.	air	excessive dust and dust accumulation at processing stations	air pollution	1	1	1	2	1	6
5.	air	too high concentration of harmful substances and dust	environmental pollution	2	2	1	3	3	11
6.	air	faulty mechanical exhausters	air pollution	3	2	2	2	3	12
7.	risk	missing or damaged personal protective equipment	environmental pollution threat to life	2	2	1	1	2	8
8.	risk	faulty or leaky installations	environmental pollution threat to life	2	2	1	1	2	8
9.	energy	high electricity consumption	depletion of non-renewable natural resources	2	1	2	3	2	10
10.	waste	incorrect storage of packaging waste	soil pollution, waste generation	1	1	1	1	2	6
11.	waste	excessive accumulation of raw materials not intended for further processing	waste generation	3	3	2	3	3	14

No.	Field of impact	Environmental aspect	Environmental impact	Category and number of points					Σ
				F	L	I	P	O	
12.	waste	too infrequent garbage collection	creation of local landfills, environmental pollution	2	1	1	2	1	7
13.	waste	a large amount of hazardous waste undergoing disposal	waste generation, environmental pollution, risk of failure	3	3	3	2	2	13

The result of the assessment is a register of aspects, combined with the input - output balance and the list of waste types (Table 11 – 13).

Table 11 – Register of significant aspects in adhesive bonding

Register of significant aspects in adhesive bonding					
No.	Environmental aspect	Field/process stage	Environmental impact	Significance criterion	Proposal for corrective action
1.	Hazardous waste	Preparatory stage Gluing	A large amount of hazardous waste undergoing disposal	High - threat to the local environment	According to the environmental program
2.	Air emissions	Primer and glue application	Air pollution, health hazard	High - impact on air quality	According to the environmental program

The analysis conducted so far referred to qualitative, descriptive assessments. It was necessary to supplement it with numerical data, what was the scale of the problems reported. In connection with this, an input-output balance was performed and the amount of substances used was determined on the scale of one year of production.

Table 12 – Input-output balance for gluing

Inputs	Outputs	Environmental impact
Semi-finished products	<ul style="list-style-type: none"> finished item volatile organic compounds 	<ul style="list-style-type: none"> hazardous waste dust fumes from the gluing process high air pollution energy consumption during the curing stage
Tools	<ul style="list-style-type: none"> adhesive material 200 l/year resin 140 l/year hardener 50 l/year packaging for hazardous substances 150 kg/year degreaser 120 l/year used contaminated materials 10 kg/year 	
Equipment	<ul style="list-style-type: none"> damaged brushes 10 kg/year damaged squeezer 2 kg/year worn-out grinding discs 2 kg/year worn-out files 1 kg/year damaged clamps 5 kg/year 	

In connection with the balance sheet carried out, which took into account the actual amounts of waste generated, a waste register was developed with the identification of properties and hazard codes (Table 13).

Table 13 – Register of hazardous waste from gluing

Process	Waste	Quantity	Properties of hazardous waste
Adhesive bonding	volatile organic compounds	No data	H6 “toxic”
	hazardous substances (adhesive material, resin, hardener, degreaser)	520 l/year	H3-A “highly flammable”
	packaging waste (pressurized cans)	150 kg/year	H1 “explosive”
	used tools made of various materials (brushes, files, grinding wheels, clamps)	17 kg/year	H2 “oxidizing”

4.4 Environmental Program

The comprehensive analysis of environmental aspects carried out using methods known from quality management influenced the acquisition of knowledge about the activities in the assembly department, where various materials are glued. The plant management also received a signal about the need to take corrective actions, signalled in various ways by employees and the plant environment. The final result of the conducted research was the development of an environmental program in relation to the significant aspect, which turned out to be hazardous waste. Two environmental goals were proposed:

- Improved handling of hazardous waste to reduce soil and water pollution.
- Minimization of air emissions – including limiting the harmful effects on employees’ health.

In connection with the goals defined in this way, the necessary tasks were developed and presented in the environmental programs shown in Table 14 and 15.

Table 14 – Environmental program for the assembly department – goal 1

Environmental program for the assembly department																	
1. Environmental goal: Improving the management of hazardous waste																	
Task	Responsible person	Estimated costs	Implementation schedule														
			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII			
Verification and completion of the safety data sheets for the given substances	Health and safety department	500 EUR			*												

Environmental program for the assembly department														
1. Environmental goal: Improving the management of hazardous waste														
Task	Responsible person	Estimated costs	Implementation schedule											
			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Training employees on the harmfulness and handling of waste	Health and safety department	3,500 EUR			*			*				*		*
Organising a waste storage site	Production Manager	4,000 EUR				*								
Purchase and labelling of appropriate containers	Supply Department	5,000 EUR		*										
Organisation of a warehouse / place for storing hazardous waste	Maintenance Manager	16,000 EUR						*	*					
Marking the place of storage of solid waste and liquids	Health and safety department	2,000 EUR							*					
Purchase of installation and start-up of ventilation and air conditioning systems	Technical Manager	30,000 EUR									*	*		
Purchase and installation of substance emission sensors	Technical Manager	10,000 EUR										*		
Installation, testing and commissioning of fire protection systems	Security Manager	20,000 EUR					*							
Establishing an emergency procedure in the event of an industrial accident	Health and safety department	2,000 EUR							*					
Signing a contract with an external company for the collection of hazardous waste	Administrative Manager	5,000 EUR				*								

Table 15 – Environmental program for the assembly department – goal 2

Environmental program for the assembly department																
2. Environmental goal: Reducing air emissions																
Task	Responsible person	Estimated costs	Implementation schedule													
			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		
Purchase of masks with filters for working with organic substances	Production Manager	600 EUR			*											
Purchase of protective aprons and gloves for working with chemicals	Supply Department	700 EUR			*											
Purchase and installation of extraction and filtration systems at the work stations	Maintenance Manager	5,000 EUR		*	*											
Carrying out additional training for employees	Health and safety department	5,000 EUR			*				*					*		

5 CONCLUSIONS

Identification and assessment of environmental aspects is a current and necessary problem in the company. In order to perform it effectively and in the shortest possible time, simple methods are needed, but they allow for logical organisation of the collected knowledge. Such methods can be the Ishikawa diagram and 5 Whys/5W2H known from quality management.

The advantages of these graphic methods are that they facilitate work by organising the transfer of information, assigning a specific hierarchy to data, ease of locating the causes of problems and the possibility of eliminating them. In connection with the systematisation of causes in designed areas, they allowed for a new perspective on known problems in gluing and the free introduction of ideas and proposals. The combination of methods also broadened the cognitive horizon and made it possible to recognize the causes in many areas: technological, organizational and employee.

As shown in the article, both the Ishikawa diagram combined with 5Whys and modified 5W2H, as well as the survey, resulted in the recognition of behaviours and practices occurring in the plant. This was the basis for further analytical work, using methods already known in environmental management. A natural continuation of the analyses performed was the preparation of the input-output

balance and the assessment of aspects related to the implementation of the environmental program project.

From a practical point of view, it can also be stated that in addition to the advantages, the proposed methods of identifying environmental nuisances and their causes using the example of gluing may have difficulties. Most often, they are concerned about the non-obvious classification of the discovered causes (they could result from various reasons) and difficulties in assigning them to the appropriate area of analysis. In addition, the causes in a more complex and extensive problem required discussion. The proposed use of an algorithm to analyse the course of the gluing process facilitated this process. Another inconvenience is the lack of reference to the importance of issues by expressing them in numbers, but this problem was solved by designing a waste balance and list. To sum up, it can be concluded that the implementation of methods from the area of quality management to environmental management is a beneficial and effective solution. This also proves that it is possible to look at already known methods in a universal way, going beyond the stereotypical approach.

ACKNOWLEDGEMENTS

The research was funded by the following projects: VIA CARPATIA Universities of Technology Network named after the President of the Republic of Poland Lech Kaczyński, under the special purpose grant from the Minister of Science, contract no. MEIN/2022/DPI/2578 “In the neighbourhood – inter-university research internships”. Ministry of Education, Research, Development and Youth of the Slovak Republic KEGA 032TUKE-4/2025 “Implementation of the results of scientific research into the elaboration of a modern university textbook – Solid Aerosols – fine and ultrafine particles in the environment”. Slovak grant project UNIVNET no. 0201/0082/19 “University and Industrial Research and Education Platform of the Recycling Society”.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest. The funders had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

DISCLOSURE OF ARTIFICIAL INTELLIGENCE ASSISTANCE

The author acknowledges the use of artificial intelligence tools in the preparation of this manuscript. Specifically, ChatGPT was utilised to support linguistic refinement and drafting of non-analytical sections. All AI-assisted content was carefully reviewed, edited, and validated by the author to ensure scholarly integrity, originality, and compliance with ethical standards. The author affirms

full responsibility for the content of the manuscript, including any material generated or supported by artificial intelligence.



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Skills Ecosystem Misalignment in Emerging Technology Sectors

DOI: 10.12776/qip.v30i1.2342

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Received: 19-02-2026 Accepted: 20-03-2026 Published: 30-04-2026

ABSTRACT

Purpose: This research investigates the misalignment between educational supply and industrial demand across emerging technology sectors in five European moderate innovator countries, aiming to understand why universities and firms struggle to co-produce the hybrid talent required for the digital transition.

Methodology/Approach: A mixed-methods comparative case study design was employed, combining desk research, focus groups, and semi-structured interviews across 35 country-sector cases in five countries and seven technology domains.

Findings: The analysis reveals a Coordination Failure Equilibrium where widespread awareness of gaps coexists with systemic inaction, highlighting severe deficits in soft skills and a critical theory-practice divide driven by a temporal mismatch between agile technology and rigid academic cycles.

Research Limitation/Implication: The findings imply that traditional degree structures are insufficient for the digital transition, necessitating a paradigm shift toward knowledge co-creation through Regional Centres of Vocational Excellence (CoVEs) and industry-validated micro-credentials.

Originality/Value of paper: This paper contributes a unique comparative analysis challenging linear human capital models by applying the Quintuple Innovation Helix framework to identify structural coordination failures rather than simple quantitative shortages.

Category: Research paper

Keywords: skills ecosystem; advanced technology skills gap; quintuple innovation helix; centres of vocational excellence

Research Areas: Management of Technology and Innovation; Quality 4.0

1 INTRODUCTION: MOTIVATION AND RESEARCH CONTEXT

The global economy is currently undergoing a structural transformation driven by the rapid convergence of digital and physical systems, often referred to as Industry 5.0 (Breque, De Nul, & Petridis, 2021). In this context, Advanced Technologies (ATIs), such as Artificial Intelligence (AI), Quantum Computing, and Blockchain, are no longer futuristic concepts but immediate drivers of industrial competitiveness and national security. However, the speed of these technological advancements has far outpaced the capacity of traditional educational systems to adapt. This creates a critical speed problem where the 3–5 year cycle of a university degree is rendered partially obsolete by the 6–12 month evolution cycles of the technologies themselves.

To understand and address this temporal mismatch, this study argues for a fundamental paradigm shift: moving from a linear lens to a systems lens. Traditional workforce development has long relied on linear human capital models, viewing education as a sequential pipeline that simply delivers graduates to the labour market (Becker, 1964). However, the complexity of the Twin Transition reveals the inadequacy of this approach. Instead, we adopt a skills ecosystem perspective (Finegold, 1999; Buchanan, Anderson, & Power, 2017), which conceptualises skill formation not as a linear output but as an emergent property of the interactions between educational institutions, industry, and policy frameworks. By applying the Quintuple Innovation Helix framework (Carayannis, Barth, & Campbell, 2012), we can analyse how the breakdown of feedback loops between these actors creates the coordination failure observed in the region.

This scientific study is empirically grounded in the extensive data collection conducted under the Erasmus+ project INVESTech (*Innovation Vocational Excellence and Sustainability in Tech*). While the primary project report (INVESTech Project, 2025) focused on a descriptive inventory of skill gaps to guide local curriculum development, this article seeks to transcend those immediate project objectives. We aim to place these empirical findings within the broader systems theoretical framework, analysing the systemic causes of misalignment rather than merely listing missing competencies. By synthesising data from the INVESTech project, this study aims to uncover the deeper coordination failures that prevent ecosystem self-correction. The primary motivation stems from a persistent disconnect observed across European moderate innovator countries: despite near-universal stakeholder awareness of skill gaps, a systemic inability to bridge them remains. Traditional perspectives often treat these gaps as simple quantitative shortages defined as too few graduates for too many jobs. This paper argues that the problem is far more insidious: it is a structural dysfunction rooted in how education, industry, and policy fail to effectively interact within a regional ecosystem. By focusing on Bulgaria, Cyprus, Greece, Lithuania, and Slovakia, this research addresses a significant but understudied region facing unique challenges in catching up with Western European technological leaders.

Furthermore, this analysis extends the theoretical discourse by incorporating Quality Management (QM) as a critical bridging competence. In the context of Industry 5.0, QM evolves into Quality 4.0, a paradigm of data-driven quality that shifts from post-production inspection to predictive quality assurance using AI and real-time sensor data. This evolution aligns with the identified skill gaps in real-time analytics and process optimisation, effectively bridging the divide between technical data engineering and managerial oversight. This study emphasises that the goal of advanced technology adoption is not merely efficiency, but the resilience and excellence of the final output; a core tenet of the Industry 5.0 framework often missed in purely technical curricula.

2 THEORETICAL FRAMEWORK: SKILLS ECOSYSTEM

To understand the persistence of skill gaps in small open economies, it is necessary to move beyond traditional, linear models of workforce development. This study adopts a multi-layered theoretical approach, integrating Skills Ecosystem Theory with the emerging literature on Regional Innovation Systems (RIS) and the transformative role of Centres of Vocational Excellence (CoVEs).

Traditional policy interventions often rely on linear human capital models (Becker, 1964), which view education as a sequential pipeline: the state invests in universities, universities produce graduates, and the labour market absorbs them. This model assumes that skill mismatches are merely market frictions. However, this linear model fails in the context of rapid technological change. It fails to account for the complexity of skill formation, where the value of a competence is determined not just by its existence, but by its deployment within a network of firms, regulations, and social institutions.

In contrast, Skills Ecosystem Theory (Finegold, 1999; Buchanan et al., 2017) conceptualises workforce development as an interconnected, organic system. An ecosystem is defined by the interdependency of actors: education providers, employers, regional governments, and workers interact to produce, demand, and regulate skills. As Uyarra (2010) argues, regional development is not just about the stock of knowledge but about the flow of knowledge between these actors. A shortcoming within the ecosystem is rarely rooted in a single institution but stems from a disruption in connectivity and feedback loops. A healthy skills ecosystem is defined by three fundamental characteristics that ensure its resilience and effectiveness (Finegold, 1999; Buchanan et al., 2017). First, it relies on coordination, ensuring that educational outputs are precisely aligned with employer requirements in terms of content, volume, and timing. Simultaneously, the system should exhibit responsiveness, demonstrating the agility to adapt curricula to technological disruptions, such as the sudden rise of Generative AI, within a timeframe of months rather than years (Capsada-Munsech & Valiente, 2020). Finally, it is anchored by inclusiveness, ensuring that multiple, overlapping pathways exist for skill acquisition, which validate diverse learning trajectories beyond the limitations of the traditional three-year degree.

Conversely, ecosystem dysfunction manifests as a low-skills equilibrium (Finegold & Soskice, 1988), where rational behaviour by individual actors leads to suboptimal collective outcomes. For example, universities may hesitate to launch niche high-tech programs due to uncertain local demand, while local firms hesitate to adopt high-tech strategies due to a lack of local talent. This chicken-and-egg deadlock is a classic example of a lack of coordination failure that linear policies cannot solve.

To break these deadlocks, the European Union has advocated Centres of Vocational Excellence (CoVEs) as institutional intermediaries. Theoretically, CoVEs represent a shift from Government to Governance. They are not mere training providers but active knowledge hubs that orchestrate the regional ecosystem (Uyarra, 2010). In the CoVE framework, the university or VET provider is no longer a monopoly educator but a network orchestrator. Their role shifts from delivering static content to facilitating a dynamic network of co-educators and trainers, including industry experts, cluster managers, and research institutes. This aligns with the Quintuple Innovation Helix model, where knowledge creation is a social process involving academia, industry, government, civil society, and the environment.

The speed problem of Industry 5.0 necessitates a move toward flexible and personalised education. Theoretical support for this shift is found in the concept of just-in-time learning and stackable credentials (OECD, 2021). The rigid, one-size-fits-all degree is increasingly viewed as an artefact of the industrial age. In a responsive ecosystem, education requires a modular structure. Micro-credentials serve as the currency of this new system, allowing learners to acquire specific, industry-validated competencies without committing to a full multi-year program. This shift redefines the university's function. It becomes a platform for lifelong learning, validating skills acquired through diverse channels – workplace training, online bootcamps, or peer-to-peer projects. As Uyarra et al. (2017) note, universities in peripheral regions can act as institutional anchors, but only if they open their boundaries to co-design curricula with regional stakeholders. By validating micro-credentials, they provide the quality assurance needed to make flexible learning portable and recognised across the labour market.

3 METHODOLOGY

This study employs a mixed-methods comparative case study design (Yin, 2018) combining desk research, focus groups, and semi-structured interviews across five European moderate innovator countries (Bulgaria, Cyprus, Greece, Lithuania, Slovakia) and seven emerging technology domains (AI & Ethics, Big Data, Blockchain, Green ICT (Information and Communication Technologies), Industry 5.0, IoT (Internet of Things), Quantum Computing). This multi-perspective approach analyses the same problem from different angles, utilising a 35-case matrix to enable robust within-country and cross-case pattern analysis across five countries and seven domains (Eisenhardt, 1989). This purposive selection targets

five countries that share common regional challenges, including post-socialist transitional legacies and the constraints of small open economies. However, they also exhibit diverse economic structures that range from the heavy industrial base of Slovakia to the service-oriented economy of Cyprus.

The research design follows the principles of methodological triangulation (Denzin, 1978; Flick, 2018) and is theoretically anchored in the regional skills ecosystem framework (Table 1). For clarity, RQ denotes the primary research question, SQ the sub-questions, and FG focus groups.

Table 1 – Research design overview

Research Question	Method	Respondents / Data Sources
Primary RQ: To what extent do skills ecosystems exhibit systematic misalignment between educational supply and labour market demand?	Triangulation across all three methods	35 country-sector cases; 71 FG participants; 24 interviews
SQ1: What is the nature and magnitude of skill gaps across seven domains?	Desk research (gap taxonomy per domain/country); focus group technical gap mapping; interview synthesis	12 EU-level and national reports; FG Table 6; Interview Table 10
SQ2: Do gaps reflect quantity, quality, or composition mismatches?	Expert interviews (graduate readiness); desk research (job role vs. degree comparison); focus groups (practitioner experience)	24 interviews across 5 countries; national labour market reports; all 5 FG reports
SQ3: Are dysfunctions uniform or do distinct national/sectoral patterns emerge?	Cross-case comparison (5 × 7 matrix); national FG reports; country desk research	Bulgaria n=12, Cyprus n=14, Greece n=22, Lithuania n=11, Slovakia n=12
SQ4: What coordination failures prevent self-correction despite awareness?	Focus groups (stakeholder diagnosis); interviews (expert analysis); desk research (repeated recommendations)	All 5 FG reports; 24 interviews; 7 domain reports

Desk research was conducted at EU and national levels, drawing on European Commission policy documents, CEDEFOP and Eurostat labour market data, national educational statistics, and industry reports. The primary data collection consisted of five focus groups, one per country; each designed as a one-day multi-stakeholder workshop (Krueger & Casey, 2015; Morgan, 1997). Participants were selected through purposive sampling (Patton, 2015), targeting industry representatives, educators, policymakers, and technology experts. In total, 71 participants took part (Bulgaria n=12; Cyprus n=14; Greece n=22; Lithuania n=11; Slovakia n=12), with a gender distribution of 32% female and 68% male. Sessions were conducted between August 2024 and January 2025.

These were complemented by 24 semi-structured expert interviews (Harvey, 2011; Mikecz, 2012), five per country (four in Bulgaria), lasting 60-90 minutes each. Interviewees included senior industry professionals, researchers, and educators, providing in-depth perspectives on technical skill requirements, institutional barriers, and future workforce needs across all seven technology domains. All

qualitative data were analysed using reflexive thematic analysis (Braun & Clarke, 2019). Ecosystem alignment was assessed across three dimensions: supply-demand match, skill composition gaps (following Becker, 1964; Acemoglu & Autor, 2011), and institutional response capacity. The combination of 35 country-sector cases, 71 focus group participants, and 24 expert interviews provides robust triangulated evidence of systemic skills ecosystem dysfunction across the region.

4 EMPIRICAL FINDINGS

The assessment focused on three critical axes. First, the Supply-Demand Match was evaluated by contrasting educational program outputs against employer-stated requirements, distinguishing between quantitative shortages (insufficient graduate numbers) and qualitative gaps (inadequate preparation). Second, the study analysed Skill Composition Gaps by categorising competencies into four distinct strata: domain-specific technical skills (e.g., AI, blockchain), regulatory and policy knowledge (e.g., GDPR – General Data Protection Regulation, ethics), soft skills (communication, adaptability), and the increasingly critical hybrid skills that span multiple domains, such as the intersection of ICT and sustainability. Finally, the institutional response capacity was evaluated by examining the speed and efficacy of the educational system's reaction to market signals, specifically looking for evidence of curriculum adaptation, the development of new programs in frontier technologies, and the robustness of industry-academia partnership mechanisms.

4.1 Critical Technical Gaps

The most immediate finding is the universality of functional deficiency. Across all 35 country-sector cases examined, not a single technology domain in any country shows adequate ecosystem alignment. This is not a matter of degree; it is categorical across all five countries and seven technology domains:

1. AI & Ethics: hybrid & regulatory gap – lack of professionals who combine technical machine learning expertise with knowledge of legal compliance (EU AI Act) and ethical frameworks.
2. Industry 5.0: human-centric gap – critical shortage of socio-technical skills, specifically human-robot collaboration, emotional intelligence, and user-centric design.
3. Big Data: specialisation deficit – abundance of general data analysts but a severe lack of architects for complex, real-time cloud infrastructure and data governance.
4. Green ICT: transdisciplinary mismatch – separation of engineering and environmental sciences prevents the training of experts in ICT-sustainability integration (ESG reporting – Environmental, Social, and Governance, energy-efficient coding).

5. IoT: theory-practice divide – graduates possess theoretical knowledge of protocols but lack applied skills in embedded systems, hardware-software integration, and operational security.

Focus groups and interviews corroborate this picture. All five national focus group reports independently identified education-industry misalignment as their primary concern, and all 24 expert interviews confirmed persistent gaps across their respective domains. The convergence across three independent methods (desk research, focus groups, and interviews), conducted separately by five national research teams, represents a strong form of triangulated evidence available in qualitative comparative research.

Table 2 – Critical technical skill gaps by country (Focus Group Data)

Domain	Bulgaria	Cyprus	Greece	Lithuania	Slovakia
AI & Ethics	Machine learning, Regulatory frameworks, Ethical AI	Machine learning, AI ethics, AI regulation	Machine learning, Regulatory frameworks	AI engineering, Deep learning, Data ethics	Coding, Machine learning, Containers
Big Data	Data governance, AI-driven insights	Data governance, Predictive modelling	Cloud computing, Big data frameworks	Data sourcing, ML, Cybersecurity	Server engineering, Real-time analytics
Blockchain	Blockchain integration, Smart contracts	Blockchain integration, Smart contracts	Smart contract development, Cryptographic security	Blockchain for traceability, Digital identity	Blockchain implementation, Encryption, Compliance
IoT	IoT architecture, Cybersecurity	IoT for sustainability, Cybersecurity	IoT security, Data analysis	IoT network management, Edge computing	IoT development, Network security

The core inference emerging from all data sources is that awareness of gaps does not generate correction. All five countries, all seven domains, and all three methods document the same dysfunction. Methodological triangulation confirms that the universal mechanism of dysfunction arises from a systemic disconnect between rapid technological change and inflexible educational cycles, yet its specific manifestation is strictly path dependent on national economic structures. As Table 2 illustrates, the specific character of these gaps mirrors local industrial specialisation, diverging from Slovakia's acute demand for hard operational engineering to Cyprus's focus on regulatory compliance and service-oriented ethics. Analysis across all data sources reveals four interrelated misalignments. These are not isolated failures, but structural features of how regional education systems relate to emerging labour markets.

1. **Disciplinary Silo Mismatch:** The labour market demands transdisciplinary competencies such as AI combined with law or Green ICT, which mono-disciplinary education systems are structurally unable to produce. Cyprus focus group participants noted that existing frameworks fail to align with

evolving needs, while interviewees identified a universal difficulty in uniting tech and business stakeholders. This creates a self-reinforcing cycle where departmental silos prevent the creation of the cross-functional graduates employers require.

2. **Theory-Practice Divide:** A consistent gap exists between theoretical knowledge and applied practice, particularly in Quantum Computing and IoT. Lithuanian participants emphasised that “technology alone is insufficient” without business integration. The structural cause lies in misaligned incentives: academic systems prioritise research over employability, and 3–5 year curriculum cycles cannot keep pace with technological changes measured in months.
3. **Specialisation Deficit:** While generalist IT skills are common, deep expertise (e.g., Rust smart contracts, quantum error correction) is rare. Small national markets create a chicken-and-egg deadlock: students avoid specialisation without guaranteed jobs, and employers do not create specialist roles without available talent, causing both sides to wait.
4. **Hybrid Skills as Highest Scarcity:** The most problematic gap involves combining distinct domains, such as Green ICT (energy plus tech) or AI & Ethics. Research indicates professionals with these dual competencies are virtually non-existent. These gaps cannot be filled by short courses; they require a fundamental redesign of qualifications, as current career pathways actively push these disciplines apart rather than together.

4.2 Soft Skill Deficits

A critical methodological strength of this study is the convergence of findings across three independent data sources: desk research, focus groups, and expert interviews. The single most consistent finding in the entire study is the universal deficit in soft skills (Table 3). This is not a minor observation buried in sector-specific reports. It appears in all seven technology domains in the desk research, in all five national focus group reports, and is confirmed by all 24 expert interviews. The consistency of both the finding and the language used to describe it constitutes the strongest evidence in the study – across independent research teams, in five countries, using three different methods.

Table 3 – Soft skill gaps confirmed across all data sources

Soft Skill	Desk Research (domains)	Focus Groups (countries)	Interviews
Communication/stakeholder engagement	7/7	5/5	All
Collaboration/teamwork	7/7	5/5	All
Adaptability/continuous learning	7/7	5/5	All
Critical thinking / problem-solving	6/7	5/5	All
Leadership/project management	6/7	4/5	All
Emotional intelligence	5/7	5/5	Majority

Focus group discussions were explicit about both the gap and its consequences. Slovakia participants noted that “non-technical skills should be more in focus as Industry 5.0 human centricity brings the strong demand for higher emotional and social intelligence”. Greek participants called for “greater emphasis on soft skills, including adaptability and interdisciplinary collaboration”. Interview synthesis described the practical damage: “ICT experts struggle to explain technical concepts to non-technical colleagues, leading to misunderstandings and slowed decision-making” (Interview Synthesis, 2024). What makes this structural unawareness rather than simply a gap is the combination of universal recognition and persistent inaction. Soft skill deficits have been documented, discussed, and recommended against in every domain and every country. Yet they remain. This points not to unfamiliarity but to a structural assumption embedded in technical education: that communication, collaboration, and adaptability are personal attributes rather than teachable competencies, and therefore not the university’s responsibility to develop formally.

4.3 National Patterns: Uniform Dysfunction, Emerging Differentiation

At the level of core dysfunction, the five countries are strikingly similar. The same four misalignment types appear in each; the same soft skill gaps are named; the same recommendations emerge from independently conducted focus groups and interviews (Table 4). This similarity is itself evidence that the problem is structural rather than country-specific, rooted in shared features of how education-industry interfaces are organised across the region rather than in any national policy failure.

Table 4 – Country-specific skill focus and emerging specialisation signals

Country	Distinctive National Focus	Emerging Specialisation Signal	Evidence
Bulgaria	Circular economy, sustainable robotics	Environmental ICT applications	Desk research emphasis
Cyprus	Blockchain governance, green energy	Fintech / digital finance hub	Master’s in digital currency
Greece	AI ethics research, public sector digitalisation	Research-intensive data roles	FG emphasis on academic collaboration
Lithuania	IoT for smart agriculture, cybersecurity in manufacturing	IoT hardware / embedded systems	Teltonika Academy
Slovakia	Smart cities, Industry 5.0, digital twin technologies	Advanced manufacturing / urban ICT	FG explicit Industry 5.0 framing

These specialisation signals are emergent rather than established. In no country has a genuine comparative advantage in any frontier technology yet consolidated. The risk is that five small markets, each attempting to develop all seven technology domains simultaneously, will produce thin, fragmented capabilities everywhere rather than deep, competitive expertise anywhere. Slovakia’s focus group articulated the systemic challenge most explicitly, invoking the Quintuple Innovation Helix: the coordination of academia, industry, government, civil society, and environment as both necessary and currently underdeveloped.

4.4 Why Self-Correction Fails: Coordination Failure Analysis

The most important question raised by this study is not what the gaps are, as they are thoroughly documented, but why they persist despite being universally known. The answer lies in four interlocking coordination failures that prevent the ecosystem from self-correcting even when all actors are aware of the problem.

The first is *disciplinary lock-in*. Universities cannot reorganise across departmental lines without dismantling faculty incentive structures tied to disciplinary research. Individual departments cannot create hybrid programs; individual faculty lack cross-boundary expertise; individual students cannot assemble transdisciplinary profiles from mono-disciplinary course menus. Simultaneously, private firms remain passive, preferring to hire “ready-made” graduates rather than investing the time and resources required to co-design curricula or co-produce talent. This is further compounded by government policy, which favours short-term, measurable project outputs over the long-term funding cycles necessary for structural reform. Together, these forces create a self-reinforcing cycle that prevents the evolution of a collaborative educational ecosystem.

The second is *the temporal mismatch*. Technology evolution now operates on a cycle of months; curriculum development and approval operate on a cycle of three to five years. By the time a new program addressing a recognised gap reaches graduating students, the specific skill needs have often already moved on. Bulgarian participants put this directly: “the education system is lagging a lot, and the market is very underdeveloped. The pace of change must be slow and systematic in the case of study programs, fast and flexible in the case of skills provision – these two levels should be seen as two distinct but complementary paths”, a contradiction that captures the impossible position education systems face.

The third is *market fragmentation*. Five small national markets cannot individually support the specialist training programs that deep technical expertise requires. A country with ten annual job openings for quantum hardware engineers cannot justify a dedicated master’s program in that domain. Aggregating demand across the region through specialisation and cooperation could solve this, but no coordination mechanism currently exists to negotiate or enforce such an arrangement.

The fourth and most revealing coordination failure is *institutional inertia* evidenced by the repetition of recommendations. Every domain report recommends “strengthen industry-academia collaboration” and “integrate soft skills into technical curricula.” These recommendations appear identically in desk research, focus groups, and interviews, conducted independently. This is not researchers discovering new solutions; it is researchers rediscovering solutions that have already been recommended, presumably before, without implementation. The recurrence of the same advice across independent sources is itself the strongest evidence that the ecosystem cannot self-correct: the knowledge of what to do is not the barrier. The ability to coordinate action across institutional boundaries is.

“We know what skills are needed. The lists are everywhere. But changing our programs takes years, and by then the technology has moved on again.” — Slovakia Focus Group participant, 2024. The barrier is not a lack of knowledge regarding necessary actions but rather the incapacity to coordinate action across institutional boundaries.

4.5 Slovakia as a Case Study of Structural Tension

Slovakia serves as a revealing case within a regional innovation system context, reflecting broader regional dynamics while also exhibiting distinctive national features that help illuminate the mechanisms of ecosystem dysfunction. To assess the functioning of the Slovak skills ecosystem, we return to the three core characteristics defined in the theoretical framework – coordination, responsiveness, and inclusiveness (Finegold, 1999; Buchanan et al., 2017). The empirical evidence indicates that although Slovakia demonstrates a well-developed conceptual awareness of these requirements, it faces persistent difficulties in operationalising them through existing institutional arrangements.

The *Coordination mechanism, which ensures educational outputs align with employer requirements*, is currently obstructed by rigid disciplinary silos. Desk research indicates that while Green IT requires a synthesis of ICT and sustainability knowledge, academic programs remain largely compartmentalised. Similarly, the transition to Industry 5.0 demands a convergence of engineering, human factors, and ethics, yet curricula are described as still evolving rather than actively adapting. This misalignment is further evidenced by the *Theory-Practice Divide*, particularly in emerging fields like Quantum Computing, which remains limited to academic research, and Blockchain, where theoretical knowledge lacks the practical smart contract experience demanded by the labour market. These patterns are consistent with earlier findings on the Slovak ICT sector, where the gap between industrial knowledge needs and educational provision has historically been shaped by path-dependent institutional arrangements that privilege traditional engineering disciplines over emerging hybrid competencies (Šebová & Hudec, 2012; Rehák, Hudec, & Buček, 2013).

Focus group participants were acutely aware of this deficit and explicitly identified the need for systemic collaboration. One participant noted: “*The cooperation of Quintuple Innovation Helix entities is crucial and inevitable to meet the needs of experts in ATIs in various training.*” The invocation of the Quintuple Innovation Helix (linking academia, industry, government, civil society, and the environment) demonstrates a high level of theoretical sophistication among Slovak stakeholders. However, the persistence of gaps suggests that while the *concept* of coordination is understood, the *mechanism* to enforce it across institutional boundaries is absent. This observation aligns with previous empirical studies on the Slovak ecosystem, which found that university-industry interactions are often driven by individual researcher initiative rather than robust, systemic transfer mechanisms (Klasová, Korobaničová, & Hudec, 2019).

Regarding *Responsiveness*, the system struggles to match the temporal pace of technological change. Interviewed experts emphasised that the acceleration of Industry 4.0 and 5.0 has created a speed problem that traditional degree cycles cannot solve. As the interview summary states: “All participants agreed that the influence of Industry 4.0 as well as 5.0 has brought not only requests for new technical skills, but also much stronger need of fast reaction from all types of educators: new courses are needed fast even for the new graduates and of course for the experienced experts.”

The domain-specific skill gaps identified in the focus group data make this institutional tension concrete. The gaps listed in Table 5 are not isolated deficiencies; they are the observable outcome of the coordination failures and path-dependent rigidities described above. Advanced machine learning, real-time analytics, smart contract development, and quantum algorithms all require applied, specialised training that the current program structure does not deliver.

Table 5 – Slovakia — Critical skill gaps by technology domain (Focus group data, Slovakia, n=12, 2024)

ATI	Slovakia-Specific Gaps
AI & Ethics	Coding, Containers (Docker), Machine learning
Big Data	Server engineering, Data pipeline design, Real-time analytics, Predictive/prescriptive analytics
Blockchain	Blockchain implementation, Encryption, Compliance
IoT	IoT development, Network security, System interoperability
ICT for Sustainability	ICT for sustainability standards, Renewable energy integration
Quantum	Quantum encryption, Quantum algorithms

When reading through the skills ecosystem framework, these domain-specific gaps reveal a consistent pattern across all three theoretical dimensions. Table 6 maps Slovakia’s performance against each dimension, distinguishing between the level of conceptual awareness demonstrated by stakeholders and the actual operational capacity of existing institutional arrangements. The divergence between these two columns is the central finding of this case study and arguably the most precise formulation of what ecosystem dysfunction looks like in practice.

Table 6 – Slovakia’s skills ecosystem — awareness vs. operational capacity (Synthesis of desk research, focus group n=12, and interview n=5 data, Slovakia, 2024)

Ecosystem Indicator	Slovakia	Regional Average	Interpretation
Awareness of Coordination Problem	High (Explicit use of Quintuple Helix model)	Medium (Implicit recognition of gaps)	Slovakia is more articulate about ecosystem dynamics and theoretical complexity.
Soft Skills Emphasis	Very High (Specific Industry 5.0 human-centric focus)	High (Universal broad demand)	Slovakia is leading the theoretical transition to Human-Centric industry requirements.
Innovation in Solutions	Medium (Advocacy for micro-credentials)	Low (Repetition of traditional policy recommendations)	Slovakia is actively experimenting with flexible formats like micro-credentials.

Ecosystem Indicator	Slovakia	Regional Average	Interpretation
Implementation Capacity	Low (Gaps persist despite high awareness)	Low (Universal stagnation)	Higher awareness has not translated into better implementation (Awareness ≠ Action).

The pattern across both tables points to the same conclusion: Slovakia's skills ecosystem is not unsuccessful due to ignorance of what is needed. It is inefficient because awareness, however sophisticated, cannot substitute for the institutional mechanisms that would translate it into coordinated action. This gap between knowing and doing (between conceptual clarity and operational capacity) is what Rehák et al. (2013) describe as the tension between path dependency and path plasticity: the system recognises the need to adapt but remains constrained by the accumulated weight of existing structures. Unlocking path plasticity in the Slovak context will require not more recommendations, but deliberate institutional redesign targeting the coordination mechanisms that currently do not exist.

5 CONCLUSIONS

This study set out to examine the extent and nature of skills ecosystem misalignment across seven advanced technology domains. Through the triangulation of 35 country-sector cases, 71 focus group participants, and 24 expert interviews, the research addresses the primary question and four sub-questions, confirming that misalignment is not a peripheral issue but a defining structural feature of the regional economy.

The investigation into the extent of ecosystem misalignment yields consistent evidence that the vast majority of cases analysed across all five countries and seven domains demonstrate a significant disconnect between educational supply and labour market demands. This prevalence points to a systemic challenge rather than incidental policy failures. This universality points to a systemic dysfunction rather than incidental policy failures. Theoretically, this challenges the assumption that skill gaps are merely temporary market frictions that self-correct over time. Instead, the persistent misalignment across diverse economies suggests a low-skills equilibrium where the feedback loops between education and industry are inhibited. This decoupling is bilateral: universities often remain trapped in disciplinary silos, unable to produce hybrid talent, while firms mostly remain trapped in a posture of passive expectation, waiting for “perfect” graduates to emerge rather than actively co-investing in the educational infrastructure required to produce them. This mutual inertia prevents the ecosystem from adapting to rapid technological shifts, leaving both sectors waiting for the other to move first.

Regarding the nature and magnitude of gaps (SQ1), the analysis identifies four distinct categories of deficiency that recur across all domains: technical specialisation deficits, absent interdisciplinary hybrids, missing soft skills, and a lack of applied experience. The most severe and theoretically significant gaps are the interdisciplinary hybrids (e.g., AI combined with Ethics, Green ICT).

Crucially, these gaps persist despite a visible layer of bottom-up activity. While the region hosts a vibrant ecosystem of hackathons, startup accelerators, and NGO-led digital initiatives, these act primarily as islands of agility. They successfully prototype solutions but lack the scale and continuity to resolve the Theory-Practice Divide at a systemic level. Consequently, the Quintuple Helix exhibits limited cohesion: the agility of the startup/NGO sector remains largely disconnected from the scale of the formal education system and the regulatory power of regional administration. The result is a fragmented landscape where pockets of excellence do not translate into a broadly skilled workforce capable of deploying technologies in production settings.

The study reveals (SQ2) that the dominant mismatch is one of composition, not quantity. While the region produces a reasonable volume of graduates in core disciplines like computer science, it fails to generate the specific types of talent required; specifically, those who combine technical depth with regulatory knowledge or applied skills. This finding has profound implications for human capital theory in the region. The dysfunction cannot be solved simply by pumping more graduates through the linear pipeline. The crisis is qualitative; the ecosystem produces mono-disciplinary specialists for a labour market that demands multi-disciplinary integrators. These findings are broadly consistent with evidence from Western European and other advanced economies, where research highlights that skill mismatches extend beyond simple quantitative shortages to include imbalances in skill utilisation, demand-side constraints, and the growing importance of soft skills (e.g., OECD, 2021; Capsada-Munsech & Valiente, 2020). However, while such patterns are also observed in more developed innovation systems, this study further demonstrates that the most critical gaps are increasingly compositional in nature, particularly the scarcity of hybrid profiles that integrate technical, regulatory, and applied competencies. In moderate innovator countries, these mismatches are amplified by weaker coordination mechanisms and slower institutional responsiveness.

The analysis of national patterns (SQ3) indicates that misalignment is strikingly uniform across Bulgaria, Cyprus, Greece, Lithuania, and Slovakia, suggesting that the problem is rooted in shared institutional features rather than specific national policies. However, signals of emerging specialisation are visible: Lithuania in deep-tech IoT, Cyprus in regulatory frameworks, and Slovakia in Industry 5.0 manufacturing. Theoretically, this highlights an implementation gap of Smart Specialisation (RIS3) strategies, which often struggle to materialise beyond formal strategic documentation. Regional administrations and national agencies have successfully drafted specialisation strategies, but have not been successful in orchestrating the ecosystem to achieve them. This lack of strategic coordination prevents any single ecosystem from achieving the critical mass needed to compete with larger Western European technological leaders.

Finally, the persistence of these gaps is explained by four specific coordination failures (SQ4): disciplinary lock-in, temporal mismatch, market fragmentation, and institutional inertia. The recurrence of the same recommendations across

independent sources confirms that the ecosystem's challenge is not diagnostic but operational. The region suffers from "projectification", an over-reliance on short-term pilots that create activity without leaving behind permanent institutional structures.

To escape this equilibrium, the regions require a transition from ad-hoc, project-based interventions to permanent institutional translation mechanisms, whether manifest as regional innovation hubs, cluster alliances, or centres of vocational excellence. These stable intermediaries operationalise the Quintuple Helix by converting abstract industry signals into concrete pedagogical action through shared governance structures, ensuring that employer needs are not merely advisory but structurally embedded in curriculum design. Furthermore, they resolve the critical temporal mismatch between rigid academic cycles and rapid technological change by implementing a two-speed architecture, where universities provide foundational depth while the agile intermediary layer facilitates industry-validated micro-credentials for immediate market responsiveness. More specifically, responsibilities should be differentiated across actors: universities should lead curriculum redesign and integration of hybrid skills; employers should co-design programs and provide work-based learning opportunities; regional authorities should coordinate ecosystem-level partnerships and specialisation strategies; and national governments should create enabling regulatory frameworks and provide long-term funding mechanisms.

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ACKNOWLEDGEMENTS

This research was supported by the Erasmus+ Programme of the European Union under the project “Innovation Vocational Excellence and Sustainability in Tech” (INVESTech) [Project No. 101103554]. The authors acknowledge the collaborative efforts of all project partners in Bulgaria, Cyprus, Greece, Lithuania, and Slovakia for their contribution to the data collection process.

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Conceptualisation, N.U., I.O.; Methodology, N.U.; Validation, I.O.; Formal analysis, N.U.; Investigation, I.O., N.U.; Resources, N.U., I.O.; Data curation, I.O.;

Original draft preparation, N.U.; Review and editing, N.U., I.O.; Supervision, N.U.; Project administration, I.O.; Funding acquisition, N.U., I.O.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest. The funders had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

DISCLOSURE OF ARTIFICIAL INTELLIGENCE ASSISTANCE

The authors acknowledge the use of artificial intelligence tools in the preparation of this manuscript. Specifically, DeepL and ChatGPT were utilised for proofreading. All AI-assisted content was carefully reviewed, edited, and validated by the authors to ensure scholarly integrity, originality, and compliance with ethical standards. The authors affirm full responsibility for the content of the manuscript, including any material generated or supported by artificial intelligence.



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From Frameworks to Feasible Practice: A Modular AI Governance Blueprint for Consulting SMEs

DOI: 10.12776/qip.v30i1.2336

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Received: 01-03-2026 Accepted: 13-04-2026 Published: 30-04-2026

ABSTRACT

Purpose: To address the growing gap between Artificial Intelligence (AI) governance expectations and the practical capacities of consulting small and medium enterprises (SMEs).

Methodology/Approach: Conceptual review and comparative analysis of leading governance regimes and standards, followed by mapping to enterprise risk management models commonly used to manage organisational risks.

Findings: The paper shows that consulting SMEs face compounded barriers (limited compliance capacity, data constraints, cultural resistance, algorithm aversion, and regulatory uncertainty) that make comprehensive governance unrealistic. It derives a modular governance blueprint that supports gradual implementation aligned with quality management and risk appetite.

Research Limitation/Implication: The blueprint requires operationalisation into checklists, templates, and measurable indicators and should be validated across multiple SME cases and AI use scenarios.

Originality/Value of paper: The key contribution is translating heterogeneous AI governance sources into a feasibility-first governance logic for SMEs, framed as a quality and trust enabler rather than a compliance-only burden.

Category: Conceptual paper

Keywords: AI risk and opportunities; management of consulting SMEs; enterprise risk frameworks; adaptive governance models; regulatory compliance innovation

Research Areas: Management of Technology and Innovation; Quality by Innovation

1 INTRODUCTION

Artificial Intelligence (AI) has transitioned from a futuristic concept to an integral element of organisational strategy and operations. This transformation brings unprecedented opportunities, but also novel risks and governance challenges. AI governance can be defined as the framework of policies, processes, and structures that ensure the ethical, safe, and accountable use of AI within organisations (Radu, 2021; Papagiannidis, Mikalef, & Conboy, 2025).

In recent years, a proliferation of AI governance frameworks has emerged at international and national levels – from high-level principles to regulatory acts and technical standards – aiming to guide the responsible development and deployment of AI. Simultaneously, risk management models are being applied and adapted to address the unique uncertainties introduced by AI technologies (Schiff et al., 2021).

Such adaptation is consistent with risk management scholarship emphasising that advances should remain grounded in risk assessment foundations and explicit treatment of uncertainty (Aven, 2016). This principles-to-practice gap is widely discussed for small and medium enterprises (SMEs) and is particularly salient in knowledge-intensive sectors such as consulting. Consulting SMEs thrive on human expertise, trust-based client relationships, and agile cultures, which create challenges for adopting and implementing AI tools. They often lack the resources and formal structures of large firms to implement comprehensive governance, while any misstep can erode client trust, a core asset in professional services (Armour & Sako, 2020). This article provides a theoretical overview of AI governance and AI-related risk management with a focus on the consulting SME context. The first part provides an overview of major AI governance frameworks: Organisation for Economic Co-operation and Development (OECD) principles, European Union (EU) AI Act, International Organisation for Standardisation/International Electrotechnical Commission (ISO/IEC) 42001:2023, National Institute of Standards and Technology Artificial Intelligence Risk Management Framework (NIST AI RMF) and their scope, principles, and implementation challenges. The following section reviews selected risk typologies and organisational risk management models relevant to AI: ISO 31000:2018, Committee of Sponsoring Organisations of the Treadway Commission Enterprise Risk Management (COSO ERM), and the Three Lines of Defence model and their contribution to AI risk management. Finally, the paper critically assesses consulting SME requirements for AI governance.

Beyond review and comparison, the paper proposes a modular AI governance blueprint for consulting SMEs. The blueprint is designed as a minimum viable governance set that can be expanded over time and mapped to external requirements (regulations and standards) and internal risk governance structures. This shifts the discussion from what responsible governance should look like in principle to what can be implemented credibly in resource-constrained professional services.

2 METHODOLOGY

This article is conceived as a theoretical overview and critical assessment of the issue of artificial intelligence governance with a specific focus on the context of small and medium-sized enterprises in the consulting sector. The methodological procedure used in this study is qualitative and interpretative, focusing on the synthesis of existing theoretical frameworks, regulatory acts, and management standards, with the goal of identifying their applicability in the practice of SMEs. The analytical approach was divided into three main phases: selection and analysis of key governance frameworks, comparative assessment of risk management models, and contextualization for the specifics of consulting SMEs.

3 EVOLUTION OF AI GOVERNANCE FRAMEWORKS

The governance of AI has evolved through a combination of soft law principles, hard law regulations, and standards developed by international bodies and governments in response to the fast-paced adoption of AI and its societal impacts (Jobin, Ienca, & Vayena, 2019; Batool, Zowghi, & Bano, 2025). This section reviews four cornerstone frameworks: the OECD AI Principles, the European Union's AI Act, the ISO/IEC 42001:2023 AI management system standard, and the NIST AI Risk Management Framework. Each reflects a different level of governance – from broad values, to binding regulation, to implementation guidance – and each entails distinct principles and challenges for implementation.

3.1 OECD AI principles

One of the first global attempts to articulate AI governance principles was led by the Organisation for Economic Co-operation and Development (OECD). In May 2019, the OECD adopted a set of AI Principles, representing the first internal standard for AI governance. These principles, endorsed by OECD members and G20 countries, were updated in 2024 to account for recent technological developments (OECD, 2024). The OECD AI Principles set out a vision for trustworthy AI. It is human-centric and aligned with democratic values. The OECD AI Principles define five value-based pillars for trustworthy AI: inclusive growth and well-being; human-centred values and fairness; transparency and explainability; robustness, security and safety; and accountability (OECD, 2024; Floridi et al., 2018).

Complementary to the principles, the OECD recommendation also calls on governments to enable trustworthy AI through investment, ecosystem-building, capacity development, agile regulation and international co-operation (OECD, 2024). The OECD AI Principles helped establish a shared vocabulary and baseline for responsible AI across jurisdictions (Radu, 2021; Jobin, Ienca, & Vayena, 2019). However, as value-based guidance, they remain non-prescriptive: their impact depends on voluntary adoption and translation into concrete organisational practices (Schiff et al., 2021).

3.2 EU AI Act

The European Union's Artificial Intelligence Act (adopted as Regulation (EU) 2024/1689) introduces a risk-based approach that classifies AI systems by risk and applies proportionate obligations, with the most extensive requirements reserved for high-risk AI (European Commission, 2021; Veale & Zuiderveen Borgesius, 2021). In brief, the Act distinguishes prohibited uses (unacceptable risk), high-risk systems subject to strict controls, limited-risk systems with transparency duties, and minimal-risk uses with few or no obligations.

For prohibited AI, the Act bans practices such as social scoring by governments and real-time biometric identification in public (with narrow exceptions) as these uses are deemed to undermine core rights (Veale & Zuiderveen Borgesius, 2021). The high-risk category includes AI in critical areas such as medical devices, hiring, credit scoring, education, transport, and law enforcement, etc. Providers of high-risk AI systems must comply with rigorous requirements before and after market deployment, including conformity assessments. Key obligations are ensuring high-quality training data (to minimise bias), technical documentation and logging for traceability, transparency to users, human oversight, robustness and cybersecurity measures, among others (European Commission, 2021). These requirements align with principles of accountability and transparency by mandating that AI systems be auditable and under meaningful human control when they significantly impact people (Floridi et al., 2018).

Substantively, the EU AI Act shifts AI governance from voluntary ethics to binding legal compliance and operationalises abstract principles into enforceable requirements for high-risk systems (e.g. documentation, human oversight and risk management) (European Commission, 2021; Floridi et al., 2018). This raises questions about definitional clarity, enforcement capacity and the balance between risk mitigation and innovation, which are particularly challenging for SMEs with limited compliance resources (Veale & Zuiderveen Borgesius, 2021).

The EU AI Act seeks balance through a field approach and by exempting low-risk innovation sandboxes. The real impact will depend on implementation details and forthcoming harmonised standards. For organisations, the AI Act effectively makes AI risk management and governance mandatory, not optional. Firms deploying AI in Europe will need internal compliance programs – including data governance, impact assessments for AI (similar to data protection impact assessments), record-keeping, and incident reporting – to meet the law's requirements (European Commission, 2021). For SMEs in particular, which often lack dedicated compliance staff, this could pose a formidable challenge, as discussed later in this article. In summary, the EU AI Act is a landmark regulatory framework translating AI governance principles into enforceable rules, though it raises questions about feasibility and support needed, especially for smaller actors, to comply (Veale & Zuiderveen Borgesius, 2021).

3.3 ISO/IEC 42001:2023 – AI management system standard

ISO/IEC 42001:2023 is the first international, certifiable AI management system standard, using a Plan-Do-Check-Act (PDCA) cycle to embed lifecycle governance and operationalise goals expressed in principles and regulation (ISO/IEC 42001, 2023; Batool, Zowghi, & Bano, 2025; Laux, Wachter, & Mittelstadt, 2024). While certification can signal assurance, consulting SMEs may benefit most from selectively adopting key controls rather than pursuing full-scale certification.

Under ISO/IEC 42001:2023, organisations implementing an Artificial Intelligence Management System (AIMS) are expected to establish policies and procedures covering the entire AI life cycle. The life cycle spans the development and acquisition of AI systems through deployment, monitoring, and decommissioning (ISO/IEC 42001, 2023). The standard emphasises key components of AI governance. Under ISO/IEC 42001:2023, organisations implement an AI Management System across the AI lifecycle by defining governance roles, integrating AI risk management (e.g. bias, safety, cybersecurity and legal compliance), embedding ethical principles, and establishing monitoring, continual improvement and stakeholder engagement processes (ISO/IEC 42001, 2023; Benraouane, 2024).

To conclude, ISO/IEC 42001:2023 is a milestone in translating AI governance principles into organisational practice. The key approach is through a management system that emphasises continuous risk management and oversight. The success of implementation will depend on providing modular and adaptive solutions.

3.4 NIST AI risk management framework (RMF) 1.0

Another major contribution to AI governance comes from the United States' National Institute of Standards and Technology (NIST), which released the AI Risk Management Framework (AI RMF) 1.0 in January 2023 (Tabassi, 2023). The NIST AI RMF is a voluntary framework intended to help organisations systematically identify, assess, and manage the risks of AI systems (Raji et al., 2020). It was developed through a multistakeholder process (industry, academia, government), building on NIST's experience with frameworks like the Cybersecurity Framework, and is envisaged as a de facto reference for AI governance best practices in the U.S. and internationally (Tabassi, 2023). The overarching aim of the NIST AI RMF is to improve the trustworthiness of AI by encouraging organisations to integrate considerations of safety, security, fairness, transparency, accountability, and privacy into the AI lifecycle (Tabassi, 2023; Floridi et al., 2018; Batool, Zowghi, & Bano, 2025).

The AI RMF is organised around four core functions that an organisation's AI risk management process should continuously perform: Govern, Map, Measure, and Manage. These are conceptually similar to phases of risk management but tailored to AI. By structuring AI risk management into these functions, the NIST

framework supports a continuous improvement loop for AI governance, rather than a one-time checklist (Tabassi, 2023). The literature has praised the AI RMF for offering a pragmatic and flexible approach that organisations can adapt to their needs (Batool et al., 2025; Radu, 2021). It does not mandate specific metrics or methods but provides a taxonomy and process that can integrate with existing risk management programs. Notably, NIST also released a companion AI RMF Playbook with suggested actions and an illustrative crosswalk mapping the AI RMF functions to other standards (like ISO/IEC 42001:2023 and the EU AI Act requirements) (Mehrabi et al., 2021; Schiff et al., 2021).

However, like any voluntary framework, its impact depends on organisational commitment. One critique is that smaller organisations might find it difficult to implement the full breadth of the framework due to resource constraints (Batool, Zowghi, & Bano, 2025). Another challenge is in the Measure function, where it can be difficult to develop meaningful metrics for complex properties such as “fairness” or “explainability”. The literature points to a need for more standardised tools and benchmarks in this area (Mehrabi et al., 2021; Schiff et al., 2021).

4 AI RISK TYPOLOGIES AND RISK MANAGEMENT MODELS FOR AI

Risk management is a well-established discipline in organisational management, providing frameworks for identifying and addressing potential events that could negatively (or positively) affect objectives. The advantage of AI introduces new risk considerations that may not be fully addressed by traditional risk management approaches. In this section, typologies of AI-related risks are outlined as identified in current literature.

4.1 Typologies of AI-related risks

AI systems present a spectrum of risks that can be categorised in various ways. A consistent theme in the literature is classifying AI risks by their nature (technical vs. non-technical) or impact area. The literature commonly groups AI-related risks into four overlapping categories: technical risks (performance, robustness and security vulnerabilities), legal/compliance risks (data protection, IP, and regulatory obligations), ethical/social risks (privacy, transparency, discrimination, and broader societal impacts), and reputational/strategic risks (trust damage, misinvestment and over-reliance) (Batool, Zowghi, & Bano, 2025; Brundage et al., 2020).

These categories often overlap. For instance, a technical risk (bias) can manifest as an ethical risk (discrimination), which then becomes a reputational risk. The EU’s risk-based approach effectively combines these considerations by focusing on the severity of impact on safety or rights (European Commission, 2021; Veale & Zuiderveen Borgesius, 2021). The literature encourages organisations to perform risk assessments specifically for AI systems. The purpose of risk

typologies is to ensure a comprehensive view: when deploying AI, one should ask – have we considered the technical reliability? The regulatory compliance? The ethical implications? The possible reputational fallout? By categorising, organisations can assign appropriate expertise to manage each (engineers for technical, compliance officers for legal, ethicists or diverse stakeholders for social, etc.).

For consulting SMEs, an additional struggle is opportunity risk – missing out on the benefits of AI (like improved efficiency or insight) can be a strategic risk in itself. Thus, many refer to “AI Risk and Opportunity Management” as a paired concept (Radu, 2021; Batool, Zowghi, & Bano, 2025). This is akin to ensuring that fear of risks does not lead to stagnation. Instead, risks are managed so that AI’s opportunities (better data analysis, enhanced services, new business models) can be seized confidently. For instance, Armour & Sako (2020) observed that professional service firms face the challenge of integrating AI into their business models (like offering AI-driven continuous services). This is a competitive advantage; not doing this could mean falling behind competitors. Therefore, governance must balance the mitigation of the risks identified above with the facilitation of innovations.

4.2 Traditional risk management frameworks applied to AI

ISO 31000:2018 defines risk as the effect of uncertainty on objectives and provides a generic process (context → identify → analyse/evaluate → treat → monitor/communicate) that can be tailored to any organisation (ISO 31000, 2018). This ISO framing aligns with risk scholarship that treats risk assessment as an iterative process linking uncertainty, evidence and decision-making (Aven, 2016). For AI, it offers SMEs a disciplined way to log AI-related uncertainties, assess likelihood and impact, and select proportionate controls or monitoring. Its limitation is generality: it does not specify AI metrics, roles or tools, so SMEs must translate it into concrete responsibilities and practices.

Organisations can leverage existing risk management frameworks to govern AI-specific risks. Three widely cited approaches are ISO 31000:2018, COSO Enterprise Risk Management (ERM), and the Three Lines of Defence model. Each framework and model offers a perspective on risk governance that remains relevant in the AI era, although some adaptation may be needed.

COSO ERM embeds risk management into strategy and performance, emphasising leadership oversight and explicit risk appetite (COSO, 2017; Fraser & Simkins, 2016). Its five components—governance & culture; strategy & objective-setting; performance; review & revision; and information, communication & reporting—support organisation-wide risk-informed decision-making. For consulting SMEs, the main value is aligning AI adoption with strategic objectives and clarifying tolerable levels of error/bias in client work, but full COSO-style implementation can be resource-intensive and therefore requires simplification (COSO, 2017).

For AI, COSO's emphasis on governance is key. It aligns with calls to treat AI risks not just as technical issues but as board-level issues, given the potential impact on company reputation and strategy (e.g. if an AI product fails, it can be as damaging as a financial misstatement) (COSO, 2017). The COSO approach would advocate that consulting SMEs define their AI risk solution (how much risk of error or bias are we willing to tolerate in our services?), involve top leadership in major AI-related decisions, and integrate AI risk metrics into their overall performance dashboards. A notable insight from COSO is linking risk to value creation – it recognises that to achieve strategic goals, taking some risk is necessary, so the goal is to manage risk in pursuit of value, not eliminate it (COSO, 2017; Fraser & Simkins, 2016). In the AI context, this resonates with the idea of leveraging AI for competitive advantage while controlling downsides. One drawback is that COSO's full implementation can be resource-intensive and formal, expecting distinct risk officers, extensive documentation, etc. (COSO, 2017; Fraser & Simkins, 2016). SMEs might not have separate compliance departments or risk committees; often, the owner or partners collectively handle these roles. So applying COSO in a small firm means simplifying – e.g. assigning one partner to champion AI risk oversight, rather than a full risk office, but still ensuring that person reports at leadership meetings about AI risk issues.

The Three Lines of Defence (3LoD) model (recently updated to the “Three Lines Model” by the Institute of Internal Auditors, 2020) provides a clear delineation of risk management roles:

- First line – operational management (people who own and manage risks in their day-to-day operations),
- Second line – risk management and compliance functions (specialists who coordinate, monitor and facilitate effective risk management),
- Third line – internal audit (providing independent assurance) (IIA, 2020).

In consulting SMEs, the first line is the project team using AI and performing day-to-day controls and review of AI-assisted outputs; the second line (a designated risk/compliance lead) sets policies, coordinates training and monitors adherence; and the third line provides independent assurance, often via periodic internal or external review (IIA, 2020; Veber, Nedomová, & Doucek, 2016). Because SME roles often merge, proportionality can be achieved through lightweight separation of duties and external checks when needed (IIA, 2020).

Table 1 – Comparison of frameworks and models in relation to AI governance for SMEs (Source: Authors)

Framework	Strengths for AI Governance	SME Relevance
NIST AI RMF	Practical, flexible, risk-focused	Scalable and modular
ISO 31000:2018	Universally adaptable, process-based	Requires tailoring, good for starters
COSO ERM	Strategic alignment, risk appetite	Governance-heavy, can be simplified
3 LoD Model	Role clarity, oversight separation	Role may be merged in SMEs, but still valuable

Each of these frameworks has something to contribute to AI governance, as indicated in Table 1. A recent analysis concluded that no single framework alone suffices for managing AI risks in SME. ISO 31000:2018 offers flexibility and processes, COSO provides strategic integration, and 3LoD offers structural clarity. Together, they form a strong foundation for managing risks and opportunities of using AI tools in everyday practice for consulting SMEs.

5 AI GOVERNANCE CHALLENGES IN CONSULTING SMES

Small and medium-sized consulting firms could significantly profit from AI tools. For instance, automating data analysis, improving predictions, or enhancing knowledge management could boost their productivity and service quality. However, these firms also face distinct governance challenges when adopting AI, compared to large organisations, as shown in Table 2 below. In this section, the paper will focus on the specific hurdles consulting SMEs encounter. Limitations are in resources and expertise, issues of trust (both within the firm and with clients), and cultural or structural factors.

Table 2 – Comparison of frameworks for AI governance in relation to AI risk management and relevance for SMEs (Source: Authors)

Framework	Strengths for AI Risk Management	SME Relevance
OECD AI Principles (2024)	Value-based orientation; explicit emphasis on accountability, robustness, transparency and human oversight; strong normative foundation for identifying ethical and societal AI risks	High-level and non-operational; suitable as a <i>conceptual compass</i> but insufficient on its own for risk implementation in SMEs
EU AI Act	Legally binding, risk-based categorisation of AI systems; explicit obligations for high-risk AI (risk management, human oversight, documentation, monitoring); strong enforcement mechanisms	High compliance burden; challenging for SMEs without legal and compliance capacity; requires simplification and external support to be feasible
ISO/IEC 42001:2023	Management-system approach to AI risks; lifecycle-based risk identification, treatment and monitoring; PDCA cycle supports continuous improvement	Scalable in principle but resource-intensive; SMEs benefit from selective or partial adoption rather than full certification
NIST AI RMF 1.0	Explicitly risk-focused; structured around Govern–Map–Measure–Manage; integrates technical and organisational risk perspectives; flexible and non-prescriptive	Highly suitable for SMEs due to modularity and adaptability; supports incremental implementation aligned with existing practices

5.1 Key barriers to AI governance implementation in SMEs

Literature and industry surveys identify a “vicious circle” of barriers that SMEs often face in adopting and governing AI (Batool, Zowghi, & Bano, 2025; Sánchez, Calderón, & Herrera, 2025). Recent evidence from IT risk management practice during Covid-19 illustrates how quickly risk processes must adapt to external

shocks, reinforcing the need for lightweight, adaptive governance (Maryška, Nedomová, & Doucek, 2020). These barriers tend to reinforce one another, making it challenging for smaller firms to break into effective AI utilisation.

The prominent obstacles include:

- **Limited Resources and Expertise:** SMEs often lack financial and specialised human resources for AI adoption, limiting their ability to implement governance best practices and increasing reliance on vendors (Sánchez, Calderón, & Herrera, 2025; Batool, Zowghi, & Bano, 2025). Fragmented data and infrastructure further reduce data quality and raise error risk (OECD, 2024; Yang, Blount, & Amrollahi, 2024);
- **Trust Issues and Algorithm Aversion:** Skepticism and algorithm aversion can lead to underuse of AI tools, duplicative work and reduced efficiency (Dietvorst, Simmons, & Massey, 2015; Logg, Minson, & Moore, 2019). In consulting contexts, reputational concerns and fear of role displacement can further increase caution (Armour & Sako, 2020; Yang, Blount, & Amrollahi, 2024);
- **Organisational Culture and Change Resistance:** Cultures built on human expertise and personalised service may resist standardisation or automation through AI, while leadership's low tolerance for failure limits experimentation (Schein, 2017; Armour & Sako, 2020). This often results in delayed adoption or minimal pilots (Batool, Zowghi, & Bano, 2025);
- **Data and Technological Constraints:** Limited data readiness (unstructured, inconsistent or poorly governed data) and legacy IT constraints reduce feasibility (OECD, 2024; Yang, Blount, & Amrollahi, 2024). From a business informatics perspective, the 'enterprise architect' role can help align data, processes and Information and Communication Technologies (ICT) governance, reducing fragmentation that undermines AI governance (Helfert, Doucek, & Maryška, 2013). Necessary upgrades and cybersecurity controls can be costly to justify without immediate returns (European Commission, 2021; Veale & Zuiderveen Borgesius, 2021);
- **Regulatory Uncertainty and Limited External Support:** Rapidly evolving AI regulation creates disproportionate uncertainty for SMEs lacking legal capacity and tailored guidance, increasing both non-compliance and over-compliance risks (Radu, 2021; OECD, 2024; Batool, Zowghi, & Bano, 2025).

Overall, these barriers reinforce one another: limited resources reduce experimentation and learning, which suppresses confidence and constrains investment. Breaking the cycle requires targeted external support, small pilot successes and education to build internal capability and trust.

5.2 Governance Challenges Specific to Consulting SMEs

Consulting SMEs operate in a context where knowledge-intensive work and personal trust constitute core value drivers. This context amplifies specific governance considerations when integrating AI:

- **Preserving Human Expertise and Tacit Knowledge:** Consulting relies on context-sensitive judgement that cannot be fully formalised; AI should therefore remain supportive rather than substitutive. Governance should enforce human-in-the-loop review for AI-assisted deliverables to protect the distinctive value of consulting advice (Schiff et al., 2021; Floridi et al., 2018);
- **Client Trust and Transparency:** AI can strengthen analytical rigour but can undermine confidence if its role is unclear or opaque. Material AI use should therefore be disclosed, and accountability for recommendations must remain explicit (Armour & Sako, 2020; Schiff et al., 2021);
- **Data Confidentiality and Ethics:** Given the sensitivity of client information, consulting SMEs need clear data boundaries, minimisation and secure processing environments; unsecured or public tools should be restricted for client data. Where safeguards cannot be ensured, AI deployment should be limited (Veale & Zuiderveen Borgesius, 2021);
- **Maintaining Personal Service Quality:** Excessive reliance on generic AI outputs may commoditise service and weaken the relational dimension. AI outputs should remain working material, with consultants shaping and contextualising final deliverables (Armour & Sako, 2020; Yang, Blount, & Amrollahi, 2024);
- **Responsibility and Liability Clarity:** Accountability does not shift to AI: consulting SMEs remain responsible for AI-assisted recommendations. Clear ownership, senior review and lightweight traceability support error handling and organisational learning without excessive burden (Schiff et al., 2021);
- **Adaptive and Modular Governance Needs:** For consulting SMEs, governance must remain proportionate: start with essential controls (data boundaries, human oversight and output quality) and expand modules as maturity grows, with periodic review to ensure practical fit (Batool, Zowghi, & Bano, 2025).

6 RESULTS AND DISCUSSION

Overall, the reviewed frameworks converge on lifecycle governance expectations (roles, oversight, documentation, and monitoring), but differ in their prescriptiveness and compliance burden (see Table 1–2). Mapped to enterprise risk governance (ISO 31000, COSO ERM and the Three Lines model), the analysis highlights a feasibility gap for consulting SMEs: comprehensive implementation is often unrealistic due to limited resources, data readiness and culture/trust constraints. To address this gap, we propose a modular, staged approach centred on a minimum viable set of controls that can be expanded as maturity grows (see Figure 1–2). This enables SMEs to capture AI benefits while maintaining client trust, accountability and service quality.

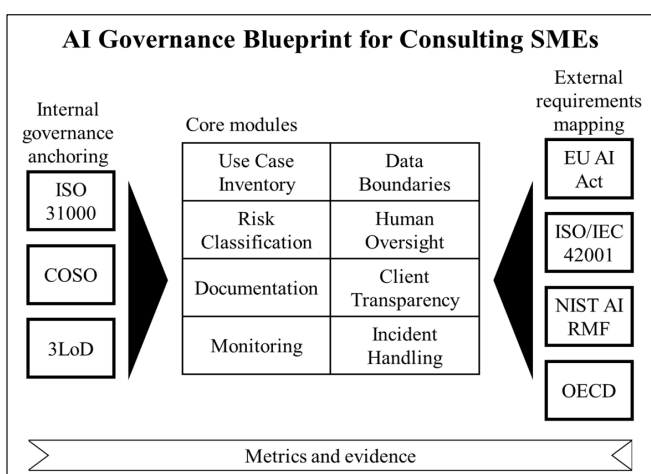


Figure 1 – Modular AI governance blueprint for consulting SMEs: Minimum viable modules and staged expansion (Source: Authors)

To operationalise the feasibility-first argument, the paper proposes a Modular AI Governance Blueprint for consulting SMEs (Figure 1). The blueprint defines a minimum viable set of governance modules (use-case inventory, data boundaries, role allocation, risk classification, human oversight, documentation and transparency, monitoring, and incident handling) that can be expanded as maturity grows. Each module is designed to map both to external governance expectations (regulation/standards) and to internal enterprise risk governance structures, enabling staged implementation without excessive bureaucracy. The blueprint’s emphasis on concrete artefacts and role allocation aligns with enterprise architecture thinking that coordinates methodologies and ICT governance across the organisation (Helfert, Doucek, & Maryška, 2013).

Table 3 – Compact operational view of the modular AI governance blueprint (Source: Authors)

Module (Core)	Objective	Minimum Practice (SME)	Artefact	Role (3 Lines of Defence)	Metric/Proxy
Use Case Inventory	Visibility of AI usage	Record use cases and their purpose	AI Use Register	1st Line Owner	% of use cases recorded
Data Boundaries	Protection of data and clients	Data classification and defined “no-go” areas	Data Governance Rules	2nd Line (Policy)	Number of breaches/incidents
Risk Classification	Proportionality	Tiering (internal and legal)	Risk Assessment Note	2nd Line	% of high-risk cases with controls implemented
Human Oversight	Output quality	Defined review checkpoints	Review Checklist	1st Line + 2nd Line	Rework rate/error rate
Documentation	Auditability	Logging of “what / when / how”	Traceability Log	1st Line	Audit pass rate
Client Transparency	Trust	Disclosure rules	Client Disclosure Note	1st Line	Number of client escalations
Monitoring	Stability	Basic performance monitoring	Metrics Register	1st/2nd Line	Drift flags per month
Incident Handling	Responsiveness	Incident logging and CAPA	Incident Record	2nd Line + 3rd Line	Time to close

Table 3 translates the dispersed requirements of major AI governance regimes into a single operational checklist designed for consulting SMEs. Instead of expecting SMEs to study and reconcile multiple frameworks, the figure decomposes governance into core modules and, for each module, specifies (i) the objective, (ii) the minimum practice that is feasible in a SME, (iii) a concrete artefact to produce, (iv) role allocation using the Three Lines model, and (v) a metric/proxy that can be tracked over time. The innovation is therefore not “another framework”, but an implementation layer that makes existing frameworks actionable under real SME capacity constraints. In practice, this reframes governance from an abstract compliance exercise into a small set of evidence-based outputs that can be reviewed, improved and, if needed, audited.

To use Table 3, a consulting SME can start by selecting a specific AI use case, or a small set of use cases, and walking through the modules row-by-row as a staged implementation path. The firm first produces the minimum artefacts (e.g., a use-case entry, basic data boundary rules, and a traceability note for AI-assisted outputs), assigns ownership using a lightweight separation of duties (first line = project delivery team; second line = designated risk/compliance lead; third line = periodic internal or external assurance), and then tracks the suggested proxies to detect early drift, quality issues, or compliance gaps. This approach is intentionally modular: SMEs can adopt the minimum viable set quickly and extend modules later as maturity grows or as regulatory/client requirements increase. Since each

module defines both “what to do” and “what to show” (artefact + metric), governance becomes easier to operationalise without building a heavy bureaucracy.

The reason for introducing this blueprint is the feasibility gap demonstrated in the paper: comprehensive governance is often unrealistic for consulting SMEs due to limited resources, fragmented data readiness, and trust-based delivery models where reputational damage is costly. Table 3 directly targets these constraints by prioritising high-impact, low-burden controls that protect service quality and client trust while keeping the workload proportionate. In other words, governance becomes a quality and trust enabler: it reduces rework caused by unreliable AI outputs, supports consistent human oversight, and increases transparency and accountability in AI-assisted deliverables. By providing a minimum viable pathway with clear responsibilities and measurable indicators— Table 3 also offers a practical starting point for continuous improvement—SMEs can iterate based on metrics rather than relying on ad hoc judgement or attempting full-scale compliance implementations from day one.

7 CONCLUSION

In conclusion, AI governance and risk management are crucial for consulting SMEs not merely as compliance tasks, but as enablers of sustainable innovation and trusted service delivery. By adopting governance measures suited to their context, these firms can benefit from AI (efficiency, better insights, and new service offerings) while safeguarding the trust and professional accountability that define their brand. The reviewed foundations provide a starting point, but the challenge remains to bridge theory and practice through proportionate, implementation-ready governance that keeps the human element at the core.

By reframing AI governance as a feasibility problem, this paper moves beyond descriptive comparison and offers a structured rationale for a minimum viable governance set for consulting SMEs. The next step is operationalisation: turning the proposed logic into templates (e.g., AI use register, data classification rules, human-review checkpoints) and validating the approach in SME pilots under real client constraints.

ACKNOWLEDGMENTS

This work was supported by grant No. IP4040 – Support for Doctoral Research at Prague University of Economics and Business.

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Conceptualisation, L.J.; Methodology, L.J.; Formal analysis, L.J.; Investigation, L.J.; Data curation, L.J.; Original draft preparation, L.J.; Visualisation, L.J.; Review and editing, P.D., L.J.; Supervision, P.D.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest. The funders had no role in the design of the study, in the collection, analysis, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

DISCLOSURE

In the preparation of this manuscript, the authors used ChatGPT-5, a generative AI tool developed by OpenAI, for translation and language correction when translating text from Czech to English. The tool was used solely to improve linguistic clarity and ensure accurate translation (with the author's corrections afterwards), without generating or altering content. All intellectual and conceptual work remains the responsibility of the authors.



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