SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2025
ORGANIZATION AND MANAGEMENT SERIES NO. 222

EVALUATION OF SELECTED INSTRUMENTS, CONCEPTS, TECHNIQUES, METHODS, TOOLS AND PRINCIPLES OF QUALITY MANAGEMENT IN THE CONTEXT OF THEIR USE IN THE CONDITIONS OF INDUSTRY 4.0

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Purpose: The purpose of the publication is to evaluate the effectiveness of selected instruments, concepts, methods, techniques, tools and principles of quality management in the context of their use in the conditions of Industry 4.0, based on the opinions of experts representing the scientific and industrial community.
Design/methodology/approach: The research used quantitative expert analysis. Thirty-three experts participated, of which 26 were selected for the final analysis (13 representing industry and 13 the scientific community). The selection of experts was based on a competence factor, taking into account self-assessment of familiarity with the subject matter and the quality of argumentation. Forty-two quality management tools and methods were evaluated using descriptive statistics and Spearman rank correlation analysis.
Findings: The results of the survey indicate that industrial practitioners and researchers differ in their preferences for the tools they use - the former focus on practical and implementation solutions, while the latter focus on analytical and conceptual tools. Despite these differences, a number of tools highly rated by both groups were also identified. Spearman correlation analysis revealed strong relationships between some methods (e.g., Scatter Diagram and Workflow, QFD and Gantt chart), suggesting the possibility of their complementary use. The results confirm the need to integrate quality management tools in an Industry 4.0 environment.
Research limitations/implications: The selection of experts, based on recommendations and self-assessment, carries a risk of subjectivity despite objective criteria. The analysis covered only 42 tools, not fully reflecting the diversity of quality management methods. The absence of strong correlations may stem from the adopted methodology and the complexity of the studied relationships. Future research should involve a broader, more diverse sample, consider industry specifics, and analyze a wider range of tools.

Originality/value: The publication provides a detailed analysis of the evaluation of the effectiveness of quality management tools under the conditions of Industry 4.0 and indicates the relationship between them. The results of the study can provide a basis for building integrated quality management systems adapted to the challenges of digital transformation.
Keywords: quality management, Industry 4.0, expert analysis, quality tools, Spearman rank correlation, digitization, innovation implementation.
Category of the paper: Research paper.

Introduction

Quality management in an enterprise, to be effective, should be characterized by the expediency and comprehensiveness of the methods, tools and principles used (Mroczko, 2012, p. 259). There are many publications in the literature on instruments, concepts, methods, tools, techniques and principles of quality management to support quality improvement in organizations. Dynamic changes resulting from the advancing Fourth Industrial Revolution, have an impact on the operation of enterprises in various areas of their activities (Janke et al., 2023; Kuzior, 2022; Saniuk, Saniuk, 2018; Spałek, 2020; Wolniak, 2023), in this area of quality management (Czyż-Gwiazda, 2024; Fadilasari et al., 2024). Therefore, it was decided in this article to check which of the selected instruments, concepts, techniques, methods, tools and principles of quality management are the most highly rated by experts from the scientific field and industry in the context of their use in the conditions of Industry 4.0. The results of the study indicate strong links between specific tools that are not widely described in the context of Industry 4.0 in the literature. In addition, differences in preferences between the academic and industrial environments were identified, and attention was drawn to the relationships between individual tools.

Literature review

The authors, by means of a literature review, identified 42 instruments, concepts, methods, tools, techniques and principles of quality management, and then sorted them according to the way they were used, using the grouping of methods proposed by Luczak and Matuszak-Flejszman, and then subjected them to further research, which is described in the empirical part of the article (Łuczak, Matuszak-Flejszman, 2007).

In the literature there are many divisions of instruments, concepts, methods, tools, techniques and principles of quality management. In order to organize the definitions in this article, the terms will be used according to the following understanding. Instruments is the broadest concept, encompassing concepts, methods and techniques (Jankowiak, 2008).

Concepts are holistic approaches involving management, within which lower levels of methods and techniques can be identified (Lichtarski, 2001). A technique is a procedure or course of action that covers specific narrow problem domains (Mazur, 2023). Methods are a specially ordered set of tools aimed at effectively achieving the intended purpose for which the method was developed (Hamrol, 2013, p. 363). Quality management tools are used to collect and process data that relates to various aspects of quality management in a company and are used to solve problems and make strategic and operational decisions (Hamrol, 2013, p. 284). The principles reflect the approach of the enterprise and its employees to quality issues in the broadest sense. The principles of quality management should be universal, transparent and known in ogranizaji employees at every level (Hamrol, 2013, p. 363).

The tools, methods and instruments of quality management can be grouped due to the methods of idea creation and planning, used for checking and control, used at the stage of evaluation of activities, used at the stage of implementation (Łuczak, Matuszak-Flejszman, 2007). Table 1. presents sets of grouped selected instruments, concepts, techniques, methods, tools and principles of quality management developed on the basis of analysis of pre-subject literature, used for creation of ideas and planning, checking and control, evaluation of activities and used at the stage of implementation.

Table 1.
Groups of selected instruments, concepts, techniques, methods, tools and principles of quality management

Method group	Instruments, concepts, techniques, methods, tools and principles of quality management
Methods for creating ideas and planning	ABCD Suzuki
	Benchmarking
	Business Process Reengineering (BPR)
	Brainstorming
	DMAIC (Define, Measure, Analyze, Improve, Control)
	Tree Diagram
	Fishbone Diagram
	Arrow Diagram
	Interrelationship Diagram
	Flowchart Diagram SIPOC (Supplier, Input, Process, Output, Customer)
	Failure Mode and Effects Analysis (FMEA)
	Multivoting
	Hoshin Kanri
	Value Stream Mapping (VSM)
	SMART method
	DMADV (Define, Measure, Analyze, Design, and Verify)
	Quality Function Deployment (QFD)
	Theory of Constrains (TOC)
	Gantt chart
Methods used for checking and controlling	5PPJ - Five-Step Quality Improvement Process
	5S Practics
	Balanced Score Card (BSC)
	Matrix Diagram
	Pareto chart
	Why-Why Diagram
	Servqual

Cont. table 1.

Methods used at the stage of evaluation of activities	5 WHY
	Scatter Diagram
	Gemba
	Is-Is Not Matrix
	Analytical Hierarchy Process (AHP)
	Poka-Yoke
	Total Quality Management (TQM)
Methods used at the implementation stage	Checksheet
	Contingency Diagram
	Workflow
	Kanban
	Measurement System Analysis (MSA)
	SMED
	Statistical Process Control (SPC)
	TPM
	Run Chart

Source: own elaboration based on: (Adamek, 2020; Arabian-Hoseynabadi et al., 2010; Dąbrowski, 2020; Drzewiecka, Stachowiak, 2014; Duplaga, 2009; Ekoanindiyo, 2014; Fortz, Thorup, 2002; Gołębiowski, 2011; Jabłoński, Jabłoński, 2011; Jolayemi, 2008; Karaszewski, 2001; Komańda, 2015; Krasiński, 2013; Król et al., 2013; Kruczek, Żebrucki, 2012; Krzemień, Wolniak, 2002; Kwintowski, 2012; Łuczak, Matuszak-Flejszman, 2007; Major, Stefanów, 2008; Malska, 2018; Michalak, 2016; Michlowicz, Świątoniowski, 2011; Obora, 2011; Otręba, Knop, 2019; Pacana et al., 2019; Randhawa, Ahuja, 2017; Rogowska, 2023; Sobczuk et al., 2021; Szczęsna, Klimecka-Tatar, 2017; Szkiel, 2023; Szydełko, Kołodziejczuk, 2016; Wawak, 2006; Wojciechowska, 2006; Wolniak, 2003; Wolniak, Sułkowski, 2018a, 2018b; Woźniak, 2008; Zwolenik, Pacana, 2019).

The presented classification highlights the diversity of quality management instruments, concepts, techniques, methods, tools and principles, and organizes them according to their main application stages. Such systematization is crucial for understanding their potential use in quality management under the conditions of Industry 4.0. In the next part of the study, an empirical analysis will be conducted to evaluate the effectiveness of these selected solutions based on expert opinions.

Methods

The purpose of the research is to evaluate selected instruments, concepts, techniques, methods, tools and principles of quality management in the context of their use in the conditions of Industry 4.0. 33 people participated in the research with experts. Expert competence was assessed on the basis of a self-assessment questionnaire, evaluating the competence coefficient (Kk) of the respondents, which is the arithmetic mean of the familiarity coefficient (Kz) and the argumentation coefficient (Ka) (Męczyńska, 2001).

$$Kk = \frac{Kz+Ka}{2} \quad (1)$$

The familiarity index (Kz) is used to determine the degree to which an expert's knowledge is consistent with the essence of the issue being analyzed. The highest values of this indicator are attributed to experts with narrow specialization. The evaluation of the expert's familiarity coefficient Kz is shown in Table 2. Its value for each expert is determined by multiplying the obtained rating from the questionnaire by a factor of 0.1.The analysis will include experts who have demonstrated sufficient knowledge of the problem, regardless of their practical involvement in solving it, i.e. achieved a Kz value of at least 0.5 (Wolniak, Sułkowski, 2018a).

Table 2.
Expert knowledge factor rating Kz

Numerical value of the assessment of the expert's knowledge of the problem	The expert's degree of familiarity with the problem
0	The expert does not know the problem
1-3	The expert has limited knowledge of the problem, but it lies within his/her area of interest
4-6	The expert has satisfactory knowledge of the problem, but does not participate in its practical solution
7-9	The expert is well acquainted with the problem and participates in its practical solution
10	The problem falls within the narrow specialisation of the expert

Source: own elaboration based on: (Wolniak, Sułkowski, 2018a).

The argumentation coefficient (Ka) is used to assess the quality of the argumentation used by the expert. The highest value is assigned to judgments based on personal experience, while the lowest value is assigned to general generalizations and intuitive opinions. This indicator is calculated by adding up the scores obtained in each category of argumentation. Experts whose argumentation is at least at an average level, corresponding to both the theoretical analysis carried out and their practical experience, i.e. Ka ≥ 0.5, will be qualified for the analysis, as shown in Table 3 (Wolniak, Sułkowski, 2018a).

Table 3.
Expert knowledge factor rating Ka

Argumentation			Source of Argumentation
High	Medium	Low	
0,3	0,2	0,1	Expert's theoretical analysis
0,5	0,35	0,2	Expert's practical experience
0,05	0,05	0,05	Generalization of works by native authors
0,05	0,05	0,05	Generalization of works by foreign authors
0,1	0,1	0,1	Expert's intuition

Source: own elaboration based on: (Wolniak, Sułkowski, 2018a).

When the minimum values of the Kz and Ka coefficients are set at 0.5 and 0.55, respectively, the qualification threshold for the competence coefficient (Kk) is determined as the average of these values. This means that an expert can be qualified for the survey if his competence coefficient is at least (0.5 + 0.55) / 2 = 0.53. Based on the Kk coefficient, 26 experts were selected, consisting of 13 respondents from industries, and 13 representing the scientific community. Those taking part in the survey were selected on the basis of recommendations.

The questions in the questionnaire made it possible to assess the phenomena studied and the relationships between them. The analysis of the results of the research concerns selected parts of the questionnaire:

- metric (5 questions, 5 variables);
- self-assessment questionnaire (2 questions, 2 variables);
- specific questions (42 questions, 42 variables).

The analysis of the obtained results was carried out using descriptive statistics, focusing on the evaluation of the frequency of responses and their percentage distribution among respondents. Particular emphasis was placed on comparing the responses of two groups of experts - representatives of the scientific community and representatives of industrial sectors - which made it possible to identify differences and similarities in the perception of the evaluated tools, methods and principles of quality management in the conditions of Industry 4.0.

The analysis of the obtained results was carried out using descriptive statistics, focusing on evaluations of the effectiveness of selected instruments, methods, techniques, tools and principles of quality management in the context of their application in the conditions of Industry 4.0. Particular emphasis was placed on interpreting the percentage distributions of responses and comparing the opinions of two groups of experts: representatives of the scientific community and practitioners from industries.

The research approach used makes it possible to capture differences and similarities in the assessments of experts representing different environments, and to identify those solutions that received the highest scores in terms of operational and strategic effectiveness in the era of digitization. In addition, Spearman's rank correlation analysis made it possible to identify strong correlations between the selected tools, which may suggest their complementarity or the possibility of simultaneous use in practice.

Results

The results presented in this section of the study reflect the opinions of two separate groups of experts: practitioners from the industrial sector and representatives of the scientific community. The respondents evaluated the effectiveness of selected tools, methods and principles of quality management in the context of their usefulness in the conditions of Industry 4.0 on the basis of the answers given to 42 specific questions. Table 4 shows the evaluation of selected instruments, techniques, methods, tools and principles of quality management in the context of their use in the conditions of Industry 4.0 with the assigned average ratings of the respondent groups.

Table 4.
Evaluation of selected quality management instruments, techniques, methods, tools and principles in the context of their use in Industry 4.0 conditions with assigned average ratings of respondent groups

Method group	Instruments, concepts, techniques, methods, tools and principles of quality management	Symbol	Industry (average)	Average for the group (Industry)	Scientists (average)	Average for the group (Scientists)
Methods for creating ideas and planning (G1)	ABCD Suzuki	P1	3,54	3,74	3,69	3,83
	Benchmarking	P2	3,69		3,69	
	Business Process Reengineering (BPR)	P3	3,62		3,69	
	Brainstorming	P4	3,31		3,31	
	DMAIC (Define, Measure, Analyze, Improve, Control)	P5	3,46		3,62	
	Tree Diagram	P6	3,85		3,92	
	Fishbone Diagram	P7	4,31		4,08	
	Arrow Diagram	P8	3,62		3,77	
	Interrelationship Diagram	P9	3,46		3,92	
	Flowchart Diagram SIPOC (Supplier, Input, Process, Output, Customer)	P10	3,38		3,85	
	Failure Mode and Effects Analysis (FMEA)	P11	3,69		3,77	
	Multivoting	P12	3,77		3,92	
	Hoshin Kanri	P13	3,69		3,69	
	Value Stream Mapping (VSM)	P14	4,38		4,46	
	SMART method	P15	3,92		4,15	
	DMADV (Define, Measure, Analyze, Design, and Verify)	P16	3,69		3,77	
	Quality Function Deployment (QFD)	P17	4,23		4,00	
	Theory of Constrains (TOC)	P18	3,69		3,62	
	Gantt chart	P19	3,69		3,92	
Methods used for checking and controlling (G2)	5PPJ - Five-Step Quality Improvement Process	P20	3,85	3,75	3,92	3,85
	5S Practics	P21	4,38		3,92	
	Balanced Score Card (BSC)	P22	3,62		3,85	
	Matrix Diagram	P23	3,54		3,85	
	Pareto chart	P24	4,00		3,62	
	Why-Why Diagram	P25	3,46		3,85	
	Servqual	P26	3,38		3,92	
Methods used at the stage of evaluation of activities (G3)	5 WHY	P27	4,00	3,68	4,00	3,88
	Scatter Diagram	P28	3,46		3,85	
	Gemba	P29	3,31		3,77	
	Is-Is Not Matrix	P30	3,46		3,69	
	Analytical Hierarchy Process (AHP)	P31	3,62		3,69	
	Poka-Yoke	P32	4,15		4,00	
	Total Quality Management (TQM)	P33	3,77		4,15	

Cont. table 4.

Methods used at the implementation stage (G4)	Checksheet	P34	3,92	3,67	3,69	3,78
	Contingency Diagram	P35	3,31		3,69	
	Workflow	P36	3,54		3,85	
	Kanban	P37	3,69		3,92	
	Measurement System Analysis (MSA)	P38	3,77		3,77	
	SMED	P39	3,85		3,62	
	Statistical Process Control (SPC)	P40	3,54		3,54	
	TPM	P41	3,92		4,00	
	Run Chart	P42	3,46		3,92	

Source: own elaboration.

Figure 1 shows the average rating of experts for groups of quality management methods.

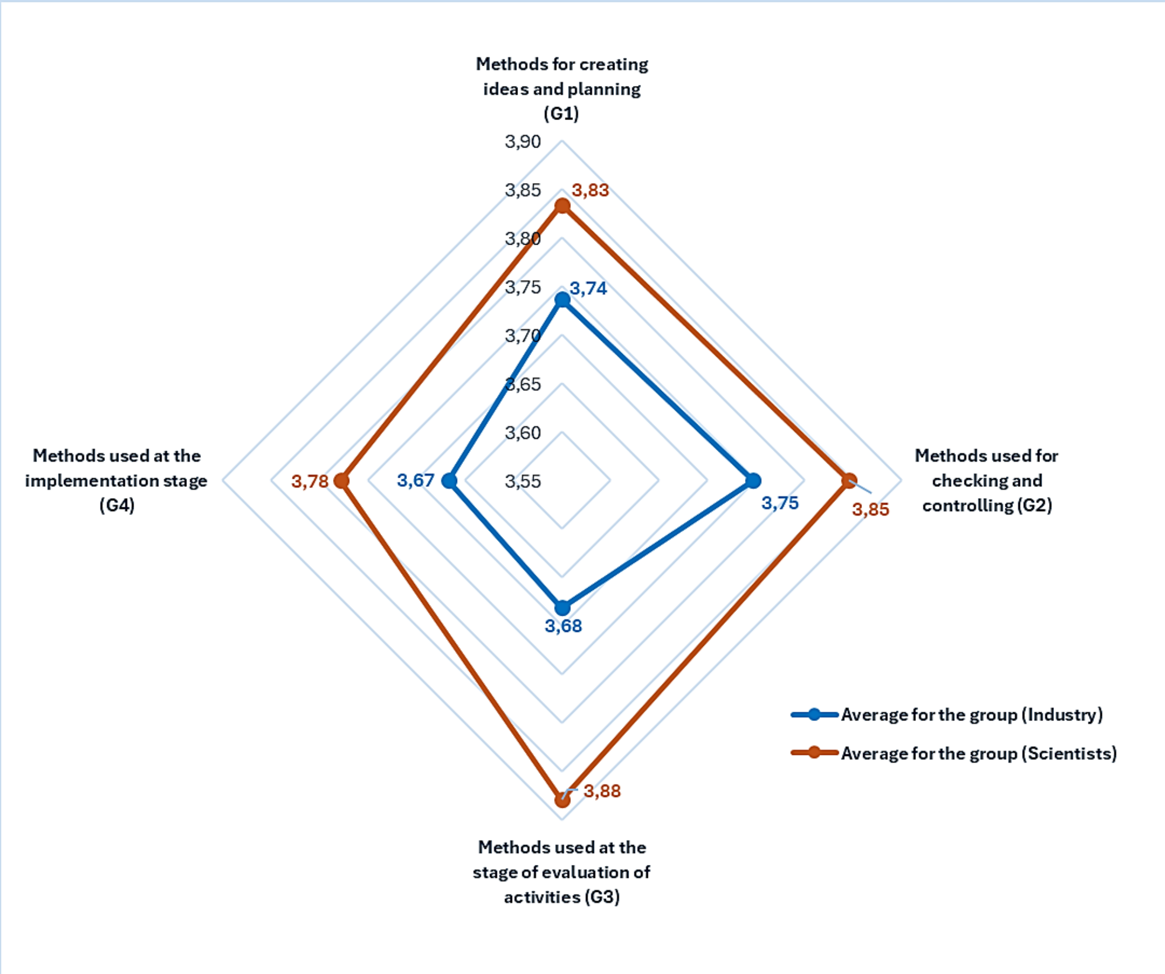

Figure 1. Average expert rating with regard to quality management groups.

Source: own elaboration.

Methods used for checking and controlling (G2) (3.75) and Methods for creating ideas and planning (G1) (3.74) were rated highest by industry experts. Next were Methods used at the stage of evaluation of activities (G3) (3.68) and Methods used at the implementation stage (G4) (3.67), which received lower ratings among this group of respondents. Based on the evaluations of industry experts, it can be concluded that they prefer practical tools that directly support daily process control and quick corrective actions.

In the Scientists group, the highest score was given to Methods used at the stage of evaluation of activities (G3) (3.88), which has great potential for analyzing process efficiency and supporting data-driven decision-making. Next in order were Methods used for checking and controlling (G2) (3.85), Methods for creating ideas and planning (G1) (3.83), and Methods used at the implementation stage (G4) (3.78). Ratings in all four groups are higher in the group of experts from the scientific world than among industry representatives.

From the difference in average ratings between the groups, it appears that academics focus more on the conceptual and systemic potential of the tools, while practitioners are more likely to be guided by their actual usefulness under time, personnel and financial constraints.

In addition, the distribution of evaluations indicates relatively small differences between the various groups of methods in both one group and the other. Thus, all four areas are important to respondents for effective quality management under Industry 4.0 conditions, and the differences are due more to the context of application than to the characteristics of the tools themselves.

Another analysis involved conducting a Spearman rank correlation analysis to determine the strength and direction of the relationship between the variables studied. The correlation coefficient indicates whether a relationship exists and the nature of the relationship. The sign of the coefficient indicates the direction of the relationship: a positive value indicates a positive dependence (an increase in one variable is associated with an increase in the other), while a negative value indicates a negative dependence (an increase in one variable is associated with a decrease in the other). The absolute value of the coefficient, on the other hand, determines the strength of the relationship. Spearman's correlation coefficient takes values between -1 and 1, where (Kulawiecka, 2016):

- 1 means positive correlation, a functional relationship,
- -1 means negative correlation, a functional relationship,
- 0 means no correlation, that is, no relationship between two variables.

The study adopted a scale with a correlation coefficient of:

- Less than |0.2| means no relationship between the studied characteristics,
- |0.2 - 0.4| means a low relationship between the studied characteristics,
- |0.4 - 0.7| means a moderate relationship between the studied characteristics,
- |0.7 - 0.9| means a significant relationship between the studied characteristics,
- Above |0.9| means a very strong relationship between the studied characteristics.

During the course of the study, 1764 pairs of variables were identified. After eliminating diagonal pairs, the number decreased to 1722. The frequency distribution of variable pairs in the correlation groups is shown in Figure 2.

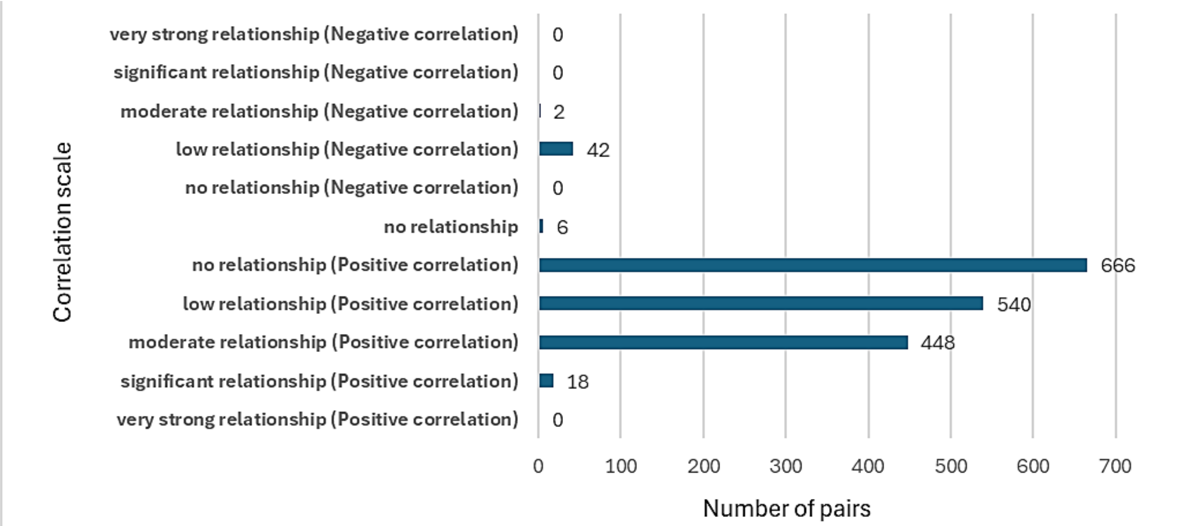

Figure 2. Frequency distribution of pairs of variables in correlation groups.

Source: own elaboration.

Figure 2 shows the frequency of pairs of variables by categories of strength and direction of correlation. The dominant category is pairs showing no significant positive correlation (n = 666), as well as pairs with low (n = 540) and moderate (n = 448) positive correlation. Negative correlations were far less frequent, mostly of low strength (n = 42), while moderate and stronger correlations were marginal (total n = 2). Both very strong positive and negative correlations were not observed. The results indicate a clear predominance of weak and moderate positive correlations and an overall low frequency of strong correlations between variables.

Due to the number of variables analyzed, only those characteristics for which the absolute value of the correlation coefficient exceeded 0.7 were selected for further analysis. Table 5 presents a summary of pairs of quality management tools and methods, assigned to the four thematic groups (G1-G4), between which a strong Spearman's rank correlation was observed, exceeding the value of 0.7. Such a result indicates a significant relationship between the variables studied - this means that these tools can be used simultaneously, complement each other or play a similar role in the analysis and improvement of processes.

Table 5.

A summary of pairs, assigned to the four subject groups (G1-G4), between which a strong Spearman rank correlation was observed, exceeding the value of 0.7

Variable 1	Group	Variable 2	Group	Correlation
P28 (Scatter Diagram)	G3	P36 (Workflow)	G4	0,88
P17 (QFD)	G1	P19 (Gantt chart)	G1	0,81
P31 (AHP)	G3	P38 (MSA)	G4	0,80
P10 (SIPOC)	G1	P19 (Gantt chart)	G1	0,77
P19 (Gantt chart)	G1	P24 (Pareto chart)	G2	0,77
P10 (SIPOC)	G1	P11 (FMEA)	G1	0,73
P16 (DMADV)	G1	P38 (MSA)	G4	0,73
P17 (QFD)	G1	P26 (Servqual)	G2	0,71
P32 (Poka-Yoke)	G3	P39 (SMED)	G4	0,71

Source: own elaboration.

The strongest correlation (0.88) was observed between P28 (Scatter Diagram), belonging to G3 (Methods used at the stage of evaluation of activities), and P36 (Workflow) from G4 (Methods used at the implementation stage). Such a high correlation suggests a close relationship between cause-effect analysis and process flow design. The implication is that organizations using analytical tools to assess the quality of processes often implement them simultaneously with tools to improve the flow of those processes.

An equally high correlation (0.81) occurred between P17 (QFD - Quality Function Deployment) and P19 (Gantt chart), both from the G1 group (Methods for creating ideas and planning). Such a relationship indicates that quality planning according to customer requirements and scheduling of project activities are complementary. In business practice, these two tools can be used together when implementing new solutions, especially in project management-oriented organizations.

A correlation of 0.80 appeared between P31 (AHP - Analytical Hierarchy Process) from G3 and P38 (MSA - Measurement System Analysis) from G4. This indicates a correlation between tools for making decisions based on established priorities and tools for ensuring the reliability of the measurement system. This means that organizations that care about the quality of measurement data are also more likely to use methods for systematically selecting and evaluating decision options.

Also at the same level of correlation (0.77) are P10 (SIPOC) and P19 (Gantt chart), both belonging to the G1 group. Such a combination indicates that overall process mapping and planning their time execution are closely related and are the foundation of effective quality project management.

A link also appears between P19 (Gantt chart, G1) and P24 (Pareto chart, G2 - Methods used for checking and controlling), where the correlation coefficient was 0.77. Effective project planning often goes hand in hand with the analysis of quality problems in terms of their impact on the bottom line, facilitating the allocation of resources to the most critical areas requiring improvement.

Significant correlations also appear between tools assigned to different groups. For example, P16 (DMADV, G1) and P38 (MSA, G4) reached a correlation of 0.73, indicating a link between the design of new solutions under the Six Sigma approach and the quality control of measurement systems necessary for accurate validation of results.

A similar value (0.73) was reached by the pair of P10 (SIPOC, G1) and P11 (FMEA, G1), which may confirm that detailed process planning and analysis of potential risks are often applied simultaneously, especially at the process design or improvement stage.

On the other hand, a correlation of 0.71 occurred between P17 (QFD, G1) and P26 (Servqual, G2), which can be interpreted as a link between designing the quality of a product or service according to customer expectations and measuring satisfaction with the realization of those expectations in practice.

A pair of P32 (Poka-Yoke, G3) and P39 (SMED, G4) ranked on the same level. Both tools are part of lean management practices and serve to reduce waste - one by eliminating errors, the other by reducing changeover times. Their joint use may be due to their focus on process optimization in manufacturing environments.

Analyzing the membership of the tools in each group, it can be seen that many strong correlations occur within the G1 (planning) group. This indicates a high degree of integration of tools used at the quality planning stage. At the same time, there is a tendency for high correlations to co-occur between tools from the G3 (evaluation) and G4 (implementation) groups, which may suggest that accurate analysis of quality data and decision-making are closely linked to the processes of implementing improvements. The identified links indicate the need to use quality tools in a complementary manner, not only within a single phase, but also between the planning, analysis, control and implementation phases. In industrial practice, this may imply the need for a more integrated approach to quality management in an Industry 4.0 environment.

Summary

The survey made it possible to assess the effectiveness of selected instruments, methods, tools and principles of quality management in the context of their application in the conditions of Industry 4.0. Analysis of the responses of 26 experts representing industrial (13 experts) and academic (13 experts) environments provided valuable information on preferences and differences in the perception of the effectiveness of individual solutions. Despite some differences in approach, it is the practitioners who focus mainly on tools that support ongoing control and implementation, while academics show more interest in analytical and conceptual solutions. A number of common elements were also identified, which demonstrate the versatility of some tools in the context of the challenges of Industry 4.0.

The use of Spearman rank correlation analysis made it possible to identify the most effective solutions and to capture correlations between them. The observed strong correlations between some tools suggest their complementarity and potential for synergistic use as part of a comprehensive approach to quality management. An example is the very strong correlation (0.88) between the Scatter Diagram tool, used to analyze cause-and-effect relationships, and the Workflow tool, used to model process flows. This correlation suggests that organizations using an analytical approach to quality assessment often implement solutions in parallel to visualize and optimize the flow of activities. An equally significant correlation (0.81) emerged between QFD (Quality Function Deployment) and the Gantt chart - planning tools that together support the design of products in line with customer expectations and the effective management of implementation time. Such strong correlations confirm the need for systemic integration of quality management tools, especially in environments characterized by high levels of complexity and dynamic operations.

The conducted research provided new information on the effectiveness and interrelationships of selected instruments, concepts, methods, techniques, tools, and principles of quality management in the context of their application in Industry 4.0. While other studies focused mainly on the evaluation of individual tools in isolated conditions (e.g. Hamrol, 2013; Wolniak, Sułkowski, 2018a), this study combined the assessment of the effectiveness of tools with an analysis of the correlations between them, taking into account the perspectives of both industrial practitioners and representatives of the scientific community.The findings also confirm that effective quality management in the era of digitization cannot be limited to the use of single methods, but requires a thoughtful selection of tools tailored to the specifics of a given process stage and organizational context, which is in line with the path of quality in digital maturity developed by Patricia Hume (Hume, 2024). Industry 4.0, through its assumptions about automation, IT integration, the Internet of Things or data analytics, creates new opportunities, but also forces a revision of existing approaches. Quality management tools should therefore not only be effective, but also flexible, interoperable and ready to work with modern technologies, as evidenced by studies conducted by other researchers (Fadilasari et al., 2024).

However, the survey is not free of limitations. The selection of experts based on recommendations and self-assessments of competence introduces the risk of subjectivity, despite the application of rigorous criteria. In addition, the analysis included only 42 selected tools, which does not exhaust the full spectrum of quality management methods available in the literature and practice. The lack of strong negative correlations and very strong positive correlations (above 0.9) may also suggest that the tools studied operate largely independently or that their relationships are too complex to be fully captured by the methodology adopted. Another limitation is the lack of consideration of industry specificity or organizational context, which may have influenced the differences in scores between groups.

Prospects for future research could include conducting quantitative surveys targeting academics as well as managers and executives from the industrial sector. An in-depth analysis of the context in which the tools are used, such as through case studies in specific companies implementing Industry 4.0, is worth considering. Additional research could also focus on the dynamics of the relationship between tools over time, and the integration of new technologies (e.g., artificial intelligence) with traditional quality management approaches. Expanding the analysis to include less researched tools or new approaches could further enrich the findings and contribute to a better understanding of their role in improving organizations in an era of digital transformation.

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