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EXTENDED BALANCED SCORECARD MODEL FOR MACHINE SAFETY WITH INTEGRATION OF INDUSTRY 4.0

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Purpose: The aim of this study was to develop and validate a model to support machine safety management by integrating an extended Balanced Scorecard (BSC) concept with solutions characteristic of Industry 4.0. A key aspect was the structuring of key factors influencing safety, their translation into key performance indicators (KPIs), and the demonstration of their interrelationships in terms of cause and effect.
Design/methodology/approach: The systemic approach employed was based on an expanded BSC model that incorporated an additional perspective: Industry 4.0. The research methodology included: the construction of a strategic model, the identification and operationalization of KPIs, a qualitative analysis of interdependencies using an impact matrix, a cause-and-effect analysis, and the development of a strategic map. The presented approach is hybrid in nature, combining elements of qualitative analysis and systems modeling.
Findings: An integrated BSC model for machine safety has been developed, identifying KPIs and their impact on the achievement of strategic objectives across the various perspectives. It has been demonstrated that the Industry 4.0 perspective acts as a catalyst, enhancing the effectiveness of initiatives in the areas of technical processes, employee safety and financial efficiency. The impact matrix and strategic map revealed strong correlations between competencies, the reliability of technical systems and economic performance
Research limitations/implications: A limitation of this study is the qualitative nature of the assessment of the relationships between KPIs and their relevance to the specific characteristics of a particular company, which limits the ability to directly generalize the results. Future research will focus on the quantitative validation of the model, its application across various industrial sectors, and an analysis of its impact on the long-term effectiveness of safety management.
Practical implications: When applied in industrial settings, the developed model can support decisions regarding maintenance, investments in digitalization, and improvements in workplace safety.
Originality/value: The key benefit lies in integrating the BSC model with the Industry 4.0 perspective in the context of machine safety, utilising performance indicators and digital technologies.

Keywords: key performance indicators (KPIs), technological security, reliability of technical systems, digitalisation of industrial processes, mechanical engineering.
Category of the paper: Research paper.

1. Introduction

Modern industrial enterprises operate in an environment of growing competition, characterised by rapid technological change and pressure to improve operational efficiency whilst ensuring a high level of workplace safety (Muller et al., 2021; Pietrewicz, 2019). The growth and development of automation, robotisation and the digitalisation of production processes have contributed to a significant increase in the complexity of technical systems, which, on the one hand, allows for higher productivity, whilst on the other generates new types of risks relating to the operation of machinery and equipment (Ingaldi, Ulewicz, 2019; Pacana, Czerwińska, 2023a). This state of affairs means that safety management ceases to be purely operational in nature and begins to function as an integral part of strategic enterprise management. This requires the use of tools enabling a comprehensive assessment and continuous improvement of safety systems, as well as taking into account regulatory and normative requirements regarding occupational safety and the operation of technical equipment (Ulewicz, Lazar, 2019; Ferrigno et al., 2023).

The complexity and dynamic nature of the contemporary operating environment for manufacturing companies necessitates the implementation of tools that enable the conduct of multidimensional assessments of a company's performance (Gajdzik, Wolniak, 2022; Pacana, Czerwińdska, 2019). Among these tools, the Balanced Scorecard (BSC) concept deserves particular attention (Krylov, 2025). The classic BSC takes into account four fundamental perspectives: financial, customer, internal processes, and learning and development. Together, these perspectives form a coherent framework that enables the translation of business strategy into specific operational actions (Wolniak, Grebski, 2023a; Armijos et al., 2025). An important feature of this tool's concept is the inclusion of both financial and non-financial indicators, which enables a more comprehensive assessment of the company's performance. The BSC aids in identifying cause-and-effect relationships between the distinct perspectives, highlighting the mechanism of value creation and the links between investments in intangible resources and the results achieved (Alanazi, 2025; Quesado et al., 2025).

The effectiveness of implementing and applying the BSC depends to a large extent on the appropriate selection of measurement tools, particularly key performance indicators (KPIs). These indicators are a fundamental element of strategy operationalisation. They enable the monitoring of the degree to which objectives are being met, the detection of deviations, and the implementation of corrective actions (Martynenko et al., 2020; Pacana, Czerwińska, 2023b). In the context of machine safety management, it is crucial to consider both outcome

KPIs, reflecting the consequences of adverse events (e.g. number of accidents, downtime costs), and leading KPIs, enabling the identification of potential hazards before they occur (e.g. near-miss incidents, the competence level of operators) (Czerwińska et al., 2025). It is also important to include indicators that allow for the assessment of compliance with safety requirements, the reliability of technical systems, and the effectiveness of preventive measures (Hu et al., 2020). The implementation of such an approach supports the transition from a reactive to a proactive safety management model, which is based on monitoring, preventing the occurrence of hazardous events, and the continuous improvement of processes (Kasprzyczak et al., 2025).

At the same time, the rapid development of the Industry 4.0 concept—which encompasses technologies such as big data analytics, the Internet of Things (IoT), artificial intelligence (AI) and cyber-physical systems—is having a significant impact on changes in the way industrial enterprises operate (Hrosul et al., 2023; Czerwińska, Pacana, 2019). The integration of production systems with digital solutions enables the ongoing monitoring of machine condition, real-time data analysis, and the prediction of potential failures and risks, which facilitates the implementation of predictive maintenance concepts and intelligent decision-support systems for safety assurance (Wolniak, Grebski 2023b; Veile et al., 2022). More broadly, the concept of Industry 4.0 is driving a shift away from traditional production models towards autonomous, intelligent and interconnected manufacturing systems, within which digital twins play a key role, enabling process simulation and the detection of risks at the virtual stage (Grabowska et al., 2019; Cruzara et al., 2023; Ni, Li, 2024). Advances in data analytics and machine learning algorithms enable adaptive process control and, in turn, their continuous optimisation. The transition towards Industry 4.0 also has an organisational dimension, which encompasses a shift in the approach to knowledge management, the development of staff competencies, and the fostering of a safety culture (Yaqub, Alsabban, 2023; Nakhal et al., 2021). Consequently, the growing importance of data and its quality necessitates the integration of information systems and the establishment of coherent management structures. This contributes to increased operational efficiency and the reliability of technical systems (Ji et al., 2024; Marcon et al., 2022).

In response to the latest trends in the development of industrial enterprises, resulting from the implementation of Industry 4.0 principles, it is appropriate to extend the classic BSC concept to include an additional perspective relating to this paradigm. Furthermore, this perspective acts as a cross-cutting factor, integrating information and technology aspects with the company's other operational areas. This approach contributes to a more comprehensive reflection of the conditions of modern industrial activity and enhances the company's ability to adapt efficiently in the face of dynamic market changes. An expanded BSC incorporating the Industry 4.0 perspective allows data from digital systems to be linked to strategic objectives and performance indicators.

Taking into account the circumstances outlined above, the aim of this study was to develop and validate a model to support the safety management of machinery and equipment, based on the integration of an extended Balanced Scorecard concept with solutions specific to the Industry 4.0 framework. A key element of the adopted approach was the identification and systematisation of the determinants of safety levels in the production environment, followed by their operationalisation in the form of a set of appropriate key performance indicators, enabling a quantitative assessment of the achievement of strategic objectives. A key aspect of the analysis was also the mapping of relationships between individual factors and the model's perspectives in the form of cause-and-effect links. The adopted approach contributes to a better understanding of the mechanisms and levers shaping the level of machine safety. The developed model supports the construction of a coherent and adaptive safety management system in an industrial enterprise.

2. Method

The development of a machine safety management model based on the extended Balanced Scorecard approach, incorporating Industry 4.0 concepts, requires the formulation of a structured research methodology. The adopted approach is based on a sequential progression from defining the model's structure, through the parameterisation of its elements, to the analysis of the cause-and-effect relationships that occur between the perspectives of the extended BSC. This approach ensures consistency between the adopted strategic objectives, KPIs and the mechanisms of their mutual interaction. The research methodology adopted has been divided into six stages.

Stage 1. Development of an extended Balanced Scorecard model – development of the analytical structure of the machine safety assurance model based on the BSC concept. Definition of the four classic BSC perspectives and introduction of an additional Industry 4.0 perspective. This additional perspective acts as a cross-cutting factor supporting the digital transformation of the machine safety management system. At the same time, strategic objectives related to ensuring and improving machine safety are defined for each of the perspectives. The result is a coherent model structure that forms the basis for its further operationalisation, as well as for the selection of appropriate KPIs.

Step 2. Identification and operationalization of KPIs – selection of appropriate KPIs based on a previously defined BSC structure. This includes both outcome indicators (e.g., failure costs, number of accidents, MTBF, MTTR) and leading indicators (e.g., near-misses, competency level, degree of digitization) to enable a comprehensive assessment of machine safety. Defining KPIs with regard to units of measurement and their significance in evaluating the achievement of established goals. Additionally, defining how Industry 4.0 technologies will be applied in data collection and analysis, which helps ensure the consistency of the measurement system and enables more effective monitoring.

Step 3. Development of a KPI impact matrix for the objectives of the extended BSC perspectives—conducting a qualitative analysis of the relationships between the selected KPIs and the objectives in the individual perspectives of the balanced scorecard. Application of a three-point rating scale to determine the strength of each KPI's impact on the achievement of strategic objectives. As a result, it is possible to identify direct and indirect relationships, as well as to identify the dominant areas of KPI influence, especially in the context of ensuring the safety and reliability of technical systems.

Stage 4. Analysis of cause-and-effect relationships—interpretation of the impact matrix from a systemic perspective, defining the relationships between KPIs and BSC perspectives. Based on this, cause-and-effect chains are identified, illustrating the relationships between individual perspectives—starting with employee competencies, through the stability of technical processes, to financial outcomes. Particular attention was paid to the role of the Industry 4.0 perspective as a catalytic factor that enhances the diagnostic, decision-making, and predictive capabilities of the safety management system.

Step 5. Development of the BSC strategic map – development of a strategic map illustrating the cascading relationships between the distinct perspectives of the expanded BSC. The map illustrates the logic of value creation across the perspectives: from learning and development to financial results. In the adopted approach, the Industry 4.0 perspective constitutes a horizontal layer that influences the other areas of the system.

Stage 6. Synthesis and interpretation of the model – integration of the results of all previous analyses and their interpretation in the context of machine safety management.

The procedure developed within the model enabled the systematic and coherent development of an extended BSc model in the area of machine safety, taking into account the concept of Industry 4.0. The adopted procedure, encompassing model construction, KPI operationalization, matrix analysis, and the identification of cause-and-effect relationships, enabled the transition from a conceptual approach to an analytical and decision-making model. As a result, a model was developed that enables a multifaceted assessment of machine safety, integrating organizational, technical, human, and digital perspectives.

3. Results and discussion

The research was conducted in close collaboration with an industrial company located in southeastern Poland and operating in the foundry industry. The company specializes in the production of metal products using partially robotized and automated production lines. The company is characterized by a high degree of complexity in its production processes, a significant proportion of high-risk operations, and intensive use of its machinery, making the area of machine and equipment safety one of the key elements of operational management.

Adopting the presented research context allowed the work to be focused on issues closely related to the management and improvement of machine and equipment safety, including hazard identification, reducing failure rates, and improving operators' working conditions. This enabled the model structure (including the extended version of the BSC, the impact matrix, and the correlated strategic map) and the proposed set of KPIs to be tailored to the specific characteristics and objectives of the company under study. The adopted approach contributed to maintaining the model's practical applicability and ensured its alignment with industrial realities.

As part of the implementation of an expanded BSC model in the area of machine and equipment safety, KPIs were developed and assigned to the model's individual perspectives. Both standard BSC perspectives and an additional perspective related to the concept of Industry 4.0 were included, reflecting trends in industrial enterprises—the growing importance of digitalization, cyber-physical systems, and data analysis in safety management. The selection of KPIs was carried out in the context of a comprehensive assessment of the safety level of machines and equipment, covering technical, economic, organizational, and competency aspects, as well as the organization's ability to respond proactively and predictively to threats. Table 1 presents the company's objectives adopted for each perspective, the corresponding KPIs, the rationale for their selection, as well as proposals for the use of Industry 4.0 tools in the context of safety monitoring and improvement.

Table 1.
A summary of key performance indicators in the extended Balanced Scorecard model for machine safety, taking Industry 4.0 into account

BSC perspective	Objective of the framework (machine safety)	KPI	Justification for KPI selection	Applications of Industry 4.0
Finance	Minimizing costs associated with accidents and machine breakdowns	- Cost of unplanned downtime [EUR/year]. - Cost of workplace accidents [EUR/year]. - Prevention effectiveness (cost of preventive measures vs. cost of breakdowns) [%].	KPIs demonstrate the economic impact of safety deficiencies and the effectiveness of preventive measures	Integration with ERP and CMMS systems; real-time cost data analysis
Customer (internal)	Ensuring a safe working environment for operators	- Number of incidents [incidents/100 employees]. - Near-miss rate [incidents/year]. - Safety perception level [%].	They reflect the actual level of safety and safety culture	Incident reporting systems (mobile apps), behavioral data analysis

Cont. table 1.

Internal processes	Improving machine reliability and operational safety	- MTBF (mean time between failures) [hours]. - MTTR (mean time to repair) [hours]. - Number of unplanned outages [events/year]. - Percentage of machines compliant with safety requirements [%].	KPIs directly relate to technical condition and the risk of failure	Predictive maintenance, IoT, machine condition monitoring
Learning and development	Developing employee skills in safe machine operation	- Number of health and safety training sessions per employee [trainings/year]. - Operators' competency level [%]. - Number of safety improvement suggestions submitted [suggestions/year].	Employee competencies are key to preventing accidents	E-learning platforms, VR/AR for training, competency analysis
Industry 4.0	Digital safety management and hazard prediction	- Percentage of machines covered by IoT monitoring [%]. - Number of predictively detected failures [events/year]. - System response time to a threat [s]. - Level of security system integration [%].	KPIs measure the level of digitalization and the ability to proactively manage safety	IoT, Big Data, AI/ML, digital twins, cyber-physical systems

Source: own study.

The summary presented in Table 1 shows the structure of an industrial enterprise's objectives and the associated indicators within the framework of an extended BSC model focused on the management of machine and equipment safety.

The financial perspective (Table 1) focuses on identifying the economic consequences of the level of machine safety and the effectiveness of preventive measures taken. The KPIs included in this perspective enable an assessment of the relationship between expenditures incurred for the prevention of failures and accidents and the costs resulting from their occurrence. This approach supports the rationalization of investment decisions in the area of technical safety and indicates that preventive measures can be a significant factor that both reduces financial losses and improves the stability of the company's operations.

The internal customer perspective (Table 1) directly concerns employees as machine users and beneficiaries of a safe work environment. The assigned KPIs enable the assessment of the actual safety level and reflect operators' perceptions, which is crucial for building safety. Including the near-miss incident rate will help identify hidden hazards and take preventive measures before situations with more serious consequences occur.

The internal processes perspective (Table 1) refers to the technical and operational aspects of machine operation that directly determine safety levels. KPIs related to equipment reliability and uptime allow for the identification of areas requiring improvement and enable the assessment of the effectiveness of maintenance activities. This approach emphasizes the importance of systematically monitoring the technical condition of machines and implementing solutions that minimize the risk of failures and unplanned downtime.

The learning and development perspective (Table 1) highlights the role of a company's human capital in ensuring the safe operation of machinery. Indicators regarding competency levels, training activity, and employee engagement in improvement initiatives underscore the importance of continuously enhancing knowledge, qualifications, and building awareness of hazards. The development of staff competencies forms the basis for the effective use of modern technologies supporting risk management and is a prerequisite for the effective implementation of safety procedures.

The additional BSC perspective related to the Industry 4.0 concept (Table 1) reflects a shift in the approach to machine safety management, moving from reactive to proactive and predictive measures. The KPIs assigned to this perspective enable the assessment of the level of process digitization and support the evaluation of an enterprise's ability to utilize real-time (or near-real-time) data for the detection and mitigation of risks. The process of integrating modern technologies—including monitoring systems, data analytics, and AI-based solutions—facilitates the creation of advanced and effective safety management systems.

As part of the analysis of the relationships between the developed KPIs and the strategic objectives of the individual perspectives of the developed BSC, the strength of their impact was assessed. This analysis allows for a transition from a static list of indicators to a relational framework, in which individual KPIs are viewed as components of a system of interrelated interactions. The adopted approach enables the identification of key levers of influence within the management of machine and equipment safety and also facilitates the identification of indicators that have the greatest impact on the achievement of the adopted objectives.

The results of the analysis are presented in Table 2 in the form of an impact matrix, which illustrates the relationships between KPIs and the objectives of the extended BSC framework, taking into account the context of digital transformation resulting from the implementation of Industry 4.0 solutions. The analysis was conducted qualitatively, using an impact scale ("+++", "++", "+") that reflects the relative strength of the impact of individual KPIs on the achievement of strategic objectives in the individual BSC perspectives.

Table 2.
Matrix of the impact of key performance indicators on goals within the framework of the sustainable scorecard perspective

KPI \ Perspective (goal)	Finance	Customer (internal)	Internal processes	Learning and development	Industry 4.0
Cost of unplanned downtime	+++		++		
Cost of workplace accidents	+++	++			
Cost of prevention vs. breakdowns	++		+		
Number of accidents	++	+++	++		
Near-miss rate		++	++	+	
Safety perception		++		++	
MTBF	++		+++		+
MTTR	++		+++		+
Number of unplanned shutdowns	+++		+++		+
Percentage of machines compliant with requirements	++	+	++		+

Cont. table 2.

Number of health and safety training sessions		+		++	+
Operator competency level	+	++	++	+++	+
Number of improvements		+	+	++	+
Percentage of machines with IoT	+		++		++
Predictively detected failures	++		+++		+++
System response time	++	+	++		+++
System integration	+		++		++

Rating: +++ – very strong impact, ++ – strong impact, + – moderate impact, blank field – no significant impact.

Source: own study.

The matrix developed (Table 1) is a tool designed to facilitate the analysis of the relationships between KPIs and strategic objectives. This map enables the identification of areas with the greatest impact on the achievement of BSC objectives and the determination of potential avenues for optimizing the machine and equipment safety measurement system within the enterprise. The distinct perspectives within the BSC do not function autonomously but are interrelated and form an interdependent system that determines the level of safety under examination.

From a systemic perspective, changes within one perspective cause cascading effects in other areas. For example, improving employee competencies and intensifying training activities (activities within the learning and development perspective) helps reduce the number of operational errors, which directly translates into a reduction in the number of accidents and an increase in process stability (internal processes perspective) and, as a result, leads to a reduction in the costs of failures and accidents (financial perspective). Similarly, the implementation of Industry 4.0 solutions enhances diagnostic and predictive capabilities in technical systems, which simultaneously improves reliability, safety, and operational efficiency.

In this context, the BSC model should be viewed as an interconnected structure in which the distinct perspectives are interrelated, and the interactions between them are nonlinear and dynamic. This approach provides a more realistic representation of the complexity of the technical safety system, within which human, organizational, technological, and economic factors are interdependent.

The developed matrix (Table 2) aids in identifying the strength and direction of the impact of the identified indicators; however, it is static in nature and does not fully capture the cause-and-effect relationships between the perspectives. For this reason, it was appropriate to create a strategic map (Figure 1), which organizes the existing relationships into a logical sequence of values. The map's structure is hierarchical (from the learning and development perspective, through internal processes and the internal customer perspective, to the financial perspective), which illustrates the logic of value creation within the enterprise. The map also accounts for the role of Industry 4.0 solutions as an aspect that strengthens the entire system.

The arrows placed within the map (Figure 1) serve as a vehicle for analytical information, facilitating the interpretation of the model's dynamics, and fulfill a dual interpretive function:

- indicating the direction of influence (cause-and-effect relationships), reflecting the flow of values and effects between perspectives,
- the symbols used (for example, "↑", "↓") concisely describe the nature of the changes (increase or decrease) and specify their consequences for subsequent BSC perspectives.

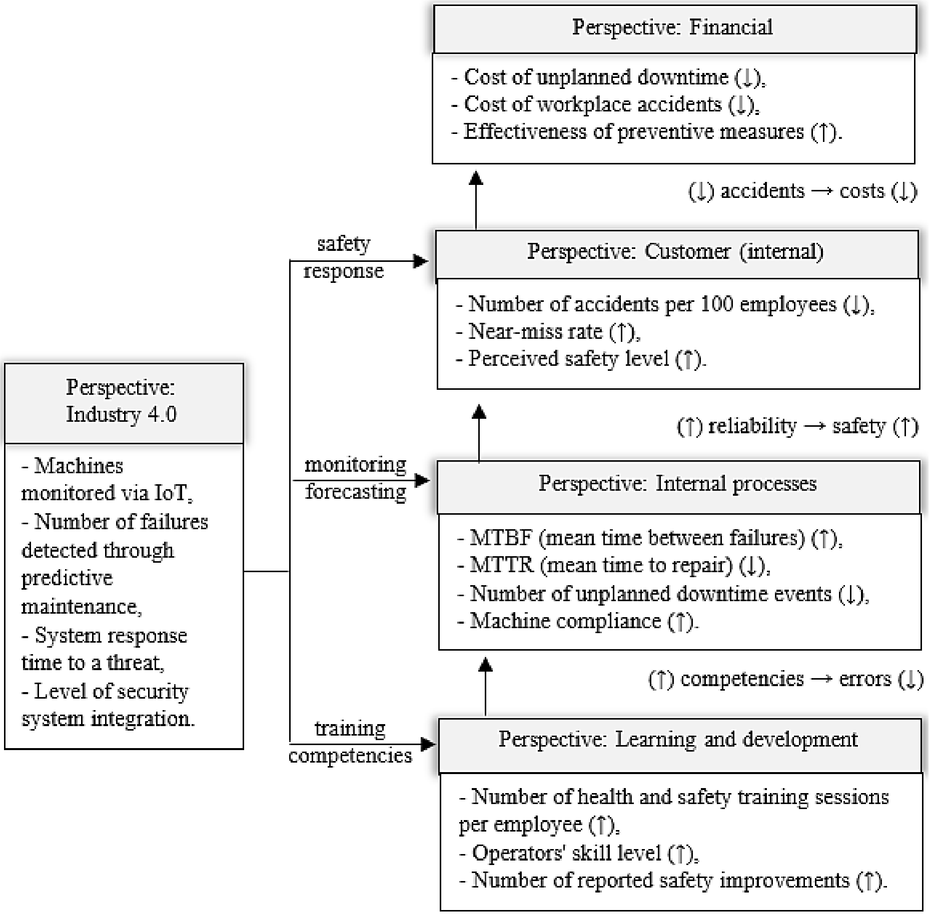

Figure 1. A strategic map of cause-and-effect relationships in the extended Balanced Scorecard model for machine safety.

Source: own study.

The learning and development perspective (Figure 1) forms the basis of the model, within which the development of employee competencies, the intensification of occupational safety and health training activities, and efforts to report improvements contribute to increased risk awareness and a reduction in human errors. These relationships are illustrated by upward-pointing arrows, indicating the transfer of effects to the internal processes perspective. From this perspective, increased operational competence results in improved technical reliability (increased MTBF, decreased MTTR), a reduction in the number of unplanned stoppages, and greater compliance of machinery and equipment with safety requirements.

Within the internal customer perspective (Figure 1), the result of stable and safe internal processes translates into a reduction in the number of accidents, an increase in the number of near-miss reports, and an improvement in the perception of safety among the company's employees. The arrows between the internal processes perspective and the internal customer indicate the direct impact of the quality of technical process execution on working conditions and personnel safety levels.

The financial perspective is positioned at the top level of the strategy map (Figure 1). This perspective aggregates the effects of previous actions. Arrows leading from lower perspectives indicate that improvements in machine safety and reliability contribute to a reduction in emergency downtime costs, a reduction in workplace accident costs, and a higher level of efficiency between prevention expenditures and failure costs. Consequently, the developed strategy map reflects the mechanism of the classic BSC (which includes four perspectives), according to which financial results are the outcome of operational and development activities.

The Industry 4.0 perspective plays a key role in the developed model; it is depicted on the strategy map (Figure 1) as an element that has a horizontal impact on other areas and acts as a catalyst for change. With regard to the internal processes perspective, technologies such as IoT and data analytics enable the monitoring of machine condition and a predictive approach to maintenance. This approach translates into fewer breakdowns and increased reliability. In relation to the internal customer perspective, these technologies improve workplace safety by enabling rapid identification of and response to hazards, and they also support the development of a safety culture. In the learning and development perspective, Industry 4.0 supports the process of enhancing employee competencies through the use of digital tools (such as e-learning or simulations). The use of these tools allows for better preparation for work in a high-tech environment. As a result, incorporating the Industry 4.0 perspective and implementing its characteristic technologies contributes to the simultaneous improvement of technical processes, increased employee safety, the development of digital competencies, and cost optimization.

Overall, both the impact matrix (Table 2) and the strategy map (Figure 1) confirm that the safety of machinery and equipment is the result of the interaction of human, technical, organizational, and digital factors. The relationships between these factors are systemic, multidirectional, and involve feedback loops.

4. Summary

The aim of this study was to develop and validate a model supporting machine safety management by integrating an extended Balanced Scorecard concept with tools and solutions characteristic of Industry 4.0. The integration of the classic BSC structure with the Industry 4.0 perspective enabled the analysis to be expanded to include issues related to monitoring, real-time data processing, and prediction, which served as a significant complement to machine safety assessment methods.

As part of the study, a set of key performance indicators (KPIs) was developed that are relevant to each of the BSC perspectives. The impact of individual KPIs on the achievement of strategic objectives was also analyzed using a dependency matrix. Based on this, key cause-and-effect relationships were identified, and the logic of interactions between the perspectives was defined, as reflected in the strategic map developed. The results obtained indicate the significant role of employee competencies and the stability of technical processes as determinants of machine safety levels, and also highlight the importance of Industry 4.0 technologies as a factor enhancing the effectiveness of decision-making and preventive actions.

The research findings can be applied in both the academic community and industrial practice, particularly in industrial enterprises with complex technological process structures. The developed model can support management and maintenance staff in making decisions regarding the safety and reliability of technical systems.

References

1. Alanazi, M.H. (2025). Strategic objectives identification and performance: an exploratory study in the context of the balanced scorecard. *Journal of Strategy and Management.* DOI: 10.1108/JSMA-05-2025-0172
2. Armijos, J.C., Juyumaya, J., Di Rocco, M., Isla, K. (2025). A Bibliometric analysis of scientific production on the balanced scorecard. *Sage Open, Vol. 15, Iss. 3.* DOI: 10.1177/21582440251375677
3. Cruzara, G., Frega, J.R., Cherobim, A.P.M.S., Sandri, E.C. (2023). Business models, dynamic capabilities and Industry 4.0: a framework to explore this relationship. *International Journal of Innovation and Technology Management*. DOI: 10.1142/S0219877023500360
4. Czerwińska, K., Pacana, A. (2019). Analysis of the implementation of the identification system for directly marked parts-DataMatrix code. *Production Engineering Archives, Vol. 23, Iss. 23.* DOI: 10.30657/pea.2019.23.04

5. Czerwińska, K., Pacana, A., Ostasz, G. (2025). A model for sustainable quality control improvement in the foundry industry using key performance indicators. *Sustainability, Vol. 17, Iss. 4.* DOI: 10.3390/su17041418
6. Ferrigno, G., Del Sarto, N., Piccaluga, A., Baroncelli, A. (2023). Industry 4.0 base technologies and business models: a bibliometric analysis. *European Journal of Innovation Management, Vol. 26, Iss. 7,* pp. 502-526. DOI: 10.1108/EJIM-02-2023-0107
7. Gajdzik, B., Wolniak, R. (2022). Influence of Industry 4.0 projects on business operations: literature and empirical pilot studies based on case studies in Poland. *Journal of Open Innovation: Technology, Market, and Complexity, Vol. 8, Iss. 1.* DOI: 10.3390/joitmc8010044
8. Grabowska, S., Gajdzik, B., Saniuk S. (2019). The role and impact of industry 4.0 on business models. *Sustainable Logistics and Production in Industry 4.0: New Opportunities and Challenges.* Springer International Publishing, pp. 31-49.
9. Hrosul, V., Galoyan, D., Mkrtchyan, T., Volosov, A., Balamut, H., Kolesnyk, A. (2023). Assessment of digital maturity, the transformation of business models in the context of digital transformation. *Reice-Revista Electronica De Investigacion En Ciencias Economicas, Vol. 11, Iss. 21*, pp. 81-105. DOI: 10.5377/reice.v11i21.16546
10. Hu, Q.J., Bai, Y., He, L.P., Cai, Q.J., Tang, S., Ma, G.L., Tan, J., Liang, B.W. (2020). Intelligent framework for worker-machine safety assessment. *Journal of Construction Engineering and Management, Vol. 146, Iss. 5.* DOI: 10.1061/(ASCE)CO.1943-7862.0001801
11. Ingaldi, M., Ulewicz, R. (2019). Problems with the implementation of Industry 4.0 in enterprises from the SME sector. *Sustainability, Vol. 12, Iss. 1.* DOI: 10.3390/su12010217
12. Ji, F., Zhou, Y.H., Zhang, H.J., Cheng, G.Q., Lou, Q.B. (2024). Navigating the digital odyssey: ai-driven business models in Industry 4.0. *Journal Of The Knowledge Economy*. DOI: 10.1007/s13132-024-02096-4
13. Kasprzyczak, L., Manowska, A., Dzwiarek, M. (2025). Cybersecurity requirements for industrial machine control systems. *Applied Sciences-Basel, Vol. 15, Iss. 3.* DOI: 10.3390/app15031267
14. Krylov, S. (2025). Integrated business analysis as a result of the development of the concept of a balanced scorecard. *Discover Sustainability, Vol. 6, Iss. 1*. DOI: 10.1007/s43621-024-00758-6
15. Marcon, E., Le Dain, M.A., Frank, A.G. (2022). Designing business models for Industry 4.0 technologies provision: Changes in business dimensions through digital transformation. *Technological Forecasting and Social Change, Vol. 185.* DOI: 10.1016/j.techfore.2022.122078
16. Martynenko, M., Lysytsia, N., Polyakova, Y., Bolotova, O. (2020). Assessment of economic activity of enterprise based on the balanced scorecard. *Financial and Credit Activity-Problems of Theory and Practice, Vol. 4, Iss. 35,* 248-257.

17. Muller, J.M., Buliga, O., Voigt, K.I. (2021). The role of absorptive capacity and innovation strategy in the design of industry 4.0 business Models-A comparison between SMEs and large enterprises. *European Management Journal, Vol. 39, Iss. 3*, pp. 333-343. DOI: 10.1016/j.emj.2020.01.002
18. Nakhal, A.A.J., Patriarca, R., Di Gravio, G., Antonioni, G., Paltrinieri, N. (2021). Investigating occupational and operational industrial safety data through Business Intelligence and Machine Learning. *Journal of Loss Prevention in the Process Industries, Vol. 73.* DOI: 10.1016/j.jlp.2021.104608
19. Ni, C.C., Li, S.C. (2024). Machine learning enabled Industrial IoT Security: Challenges, Trends and Solutions. *Journal of Industrial Information Integration, Vol. 38.* DOI: 10.1016/j.jii.2023.100549
20. Pacana, A., Czeriwńska, K. (2025). Validation of the use of KPIs to measure information security management system performance in manufacturing companies. *Production Engineering Archives. Vol. 31, Iss. 2,* pp. 266-275. DOI: 10.30657/pea.2025.31.26
21. Pacana, A., Czerwińska, K. (2023a). Analysis of the use of agile methods, tools and techniques in foundry enterprises. *System Safety: Human-Technical Facility-Environment, Vol 5, Iss. 1,* pp. 1-9. DOI: 10.2478/czoto-2023-0001
22. Pacana, A., Czerwińska, K. (2023b). A quality control improvement model that takes into account the sustainability concept and KPIs. *Sustainability, Vol. 15, Iss. 12.* DOI: 10.3390/su15129627
23. Pacana, A., Czerwińska, K., Grebski, M.E. (2022). Analysis of development processes effectiveness using KPI. *Zeszyty Naukowe Organizacja i Zarządzanie, Vol. 157.* Politechnika Śląska, pp. 387-396.
24. Pacana, A., Czerwińska, K. (2019). Model of diagnosing and searching for incompatibilities in aluminium castings. *Materials, Vol. 14, Iss. 21*. DOI: 10.3390/ma14216497
25. Pietrewicz, L. (2019). Technology, Business Models and Competitive Advantage in the Age of Industry 4.0. *Problemy Zarzadzania-Management Issues, Vol. 17, Iss. 2*, pp. 32-53. DOI: 10.7172/1644-9584.82.2
26. Quesado, P., Oliveira, HC., Silva, R. (2025). Integrating sustainability goals into the balanced scorecard: a bibliometric analysis of the sustainability balanced scorecard. *Measuring Business Excellence, Vol. 29, Iss. 2,* 352-367. DOI: 10.1108/MBE-09-2024-0139
27. Ulewicz, R., Lazar, L.V. (2019). The effect of lean tools on the safety level in manufacturing organisations. *System Safety: Human-Technical Facility-Environment, Vol. 1, Iss. 1.*
28. Veile, J.W., Schmidt, M.C., Voigt, K.I. (2022). Toward a new era of cooperation: How industrial digital platforms transform business models in Industry 4.0. *Journal of Business Research, Vol. 143,* pp. 387-405. DOI: 10.1016/j.jbusres.2021.11.062

29. Yaqub, M.Z., Alsabban, A. (2023). Industry-4.0-enabled digital transformation: prospects, instruments, Challenges, and implications for business strategies. *Sustainability, Vol. 15, Iss. 11.* DOI: 10.3390/su15118553
30. Wolniak, R., Grebski, W. (2023a). The usage of statistical Balanced Scorecard in Industry 4.0 conditions. *Zeszyty Naukowe Politechniki Śląskiej, Organizacja i Zarządzanie, Vol. 189,* pp. 771-781.
31. Wolniak, R., Grebski, W. (2023b). Work safety and health–the business analytics usage in Industry 4.0 conditions. *Scientific Papers of Silesian University of Technology. Organization & Management [Zeszyty Naukowe Politechniki Slaskiej. Seria Organizacji i Zarzadzanie, Vol. 186,* pp. 705-716.