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SAFETY MODELING IN AN AUTOMATED PRODUCTION ENVIRONMENT USING KPIs

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Andrzej Pacana[1] – *orcid id: 0000-0003-1121-6352, e-mail: app@prz.edu.pl*
Karolina Czerwińska[2] – *orcid id: 000-0003-2150-0963, e-mail: k.czerwinska@prz.edu.pl*
[1,2]Rzeszow University of Technology; Faculty of Mechanical Engineering and Aeronautics, **Poland**

Abstract: With the increasing automation of production processes, there is a growing need for systematic monitoring of the safety and effectiveness of operational activities, which requires the use of appropriate performance indicators. The aim of the study was to develop a model for identifying key performance indicators (KPIs) for production and operational safety in an automated manufacturing environment. The research was based on a review of scientific literature, surveys, and nominal meetings with industrial safety experts. The identified KPIs were divided into three groups: preventive, monitoring, and result indicators. This approach enables multifaceted analyses covering preventive measures, ongoing monitoring, and evaluation of the effectiveness of implemented countermeasures. The proposed solution contributes to increasing employee safety, machine reliability, and the continuity of the entire enterprise. The verification of the proposed model confirmed its usefulness and practical applicability. The developed model can provide practical support for production engineers, safety specialists, and those responsible for system development in industrial organizations. Future research may focus on enriching the model with predictive solutions using advanced data analytics and machine learning methods.

Keywords: Industry 4.0, key performance indicators (KPIs), safety parameter monitoring, management, and quality

1. INTRODUCTION

Contemporary production plants operate in conditions of growing competition and dynamic market changes. The pressure to increase production efficiency, improve product quality, and shorten order fulfillment times determines the need to implement modern technological solutions while ensuring the safety of employees and processes (Saniuk, et al. 2020; Gajdzik and Wolniak, 2022).

Currently operating industrial entities are increasingly relying on automated manufacturing systems that combine high efficiency with a growing degree of process complexity. The implementation of numerically controlled machines, industrial robots, and integrated control systems enables the execution of increasingly complex operations while simultaneously increasing production efficiency (Gangoiti et al., 2021; Ye, et al., 2020;

Wang and Hu, 2020). Automation allows for shorter production cycles, reduced costs, and improved product quality by eliminating errors resulting from manual labor (Hetmanczyk, 2024; Pacana and Czerwińska, 2025a). However, the implementation of complex robotic processes and control systems increases the risk of technical failures, operational errors, production downtime, and safety hazards for employees. The complexity of these modern industrial conditions contributes to the fact that potential irregularities may become more difficult to detect (Kampa and Golda, 2018; Pacana and Czerwińska, 2025b). In such conditions, it is necessary to use advanced methods of monitoring, control, and risk assessment that enable early identification of deviations. This allows for quick corrective action and ensures stable and safe operation of the plant (Lievano-Martinez, et al., 2022).
The issue of safety in automated environments covers many interrelated areas concerning the technical and organizational aspects of a manufacturing company's operations (Pacana, et al., 2021). In particular, it concerns production and operational safety, which are essential for maintaining process continuity, reducing the risk of downtime, and ensuring optimal work organization in a modern technology environment (Zwetsloot and Ashford, 2003; Kopczewski and Smal, 2017).
Production safety concerns the reliability of machines, equipment, and manufacturing processes, as well as reducing the risk of failures that could interrupt the manufacturing process (Bourassa, et al., 2016). This type of safety includes preventive measures such as monitoring the technical condition of machines, maintaining equipment, controlling production process parameters, and performing regular diagnostics of automation systems. Early detection of potential irregularities makes it possible to reduce the risk of failures, minimize production losses, and ensure continuity of order fulfillment (Malysa and Furman, 2021; Aziz, et al., 2014).
In the context of ensuring safety, in addition to technical aspects, organizational safety is equally important, focusing on protecting employees, complying with procedures and standards, and minimizing the risk of accidents and incidents in the workplace. It includes training practitioners in safe work practices and supervising compliance with health and safety procedures, including controlling access to hazardous areas (Caruana and Francalanza, 2021). It also concerns the use of appropriate personal protective equipment and the implementation of hazard reporting mechanisms. Effective operational safety management is based on close cooperation between production, maintenance, and safety departments, which enables rapid detection of hazards and immediate response in critical situations (Behie, et al., 2020; Javed, et al., 2021).
Effective management of production and operational safety requires an integrated approach combining technical, organizational, and process aspects. This means that control and preventive measures should address both the stability of technological processes and the reliability of machinery and equipment, as well as the creation of appropriate organizational procedures, staff training, and monitoring of safety compliance (Brocal, et al., 2018; Qiao, et al., 2022). Such a comprehensive approach will ensure consistency of actions within the company, increasing employee safety. In this context, key performance indicators (KPIs) become an important tool for monitoring safety levels, evaluating the effectiveness of preventive measures, and supporting improvement processes within the company (Ortiz-Espinoza, et al., 2021). KPIs allow for systematic tracking of preventive measures and ongoing operations, enabling early identification of irregularities, reduction of failure risk, and decision-making based on objective data. KPIs also enable the comparison of results over time, which facilitates the detection of areas

requiring improvement and the optimization of security procedures (Pasman and Rogers, 2014).
Integrating relevant KPIs with modern digital systems typical of Industry 4.0 brings benefits in the form of increased monitoring efficiency and decision-making quality (Leveson, 2015). Automation in the collection of data from machines, sensors, and production process monitoring systems makes it possible to analyze trends on an ongoing basis, identify potential risks, and evaluate the effectiveness of the procedures involved (Wang, et al., 2024; Pacana et al., 2025). As a result, KPIs cease to be merely reporting tools and become an active link supporting safety management, production process optimization, and risk minimization.
The aim of the study was to develop a model for identifying key performance indicators (KPIs) for production and operational safety in an automated manufacturing environment. The proposed approach aims to indicate how to select, classify, and implement indicators that can be used to assess the effectiveness of preventive measures, monitor current risks in production processes, and evaluate the performance of the safety system.
The originality of the article lies in the development of a KPI model for safety in an automated production environment, integrating preventive, monitoring and outcome indicators. The model combines a theoretical approach with practical survey research and expert consultations, ensuring both scientific reliability and operational usefulness. It takes into account the specific nature of Industry 4.0 and creates a basis for further predictive development using data analytics and machine learning.

2. METHOD

Effective safety management in modern enterprises requires the use of assessment methods that guarantee high reliability and independence of results. In order to obtain reliable and comparable results, it is necessary to precisely define the methods of measuring the effectiveness of protective solutions used in the area of production and operational safety. The process of determining the appropriate set of indicators (KPIs) should take into account available resources, including staff competencies, financial capabilities, and existing technical infrastructure.
A model for assessing the level of safety in manufacturing companies has been developed based on the identification and use of key performance indicators. The process of selecting appropriate KPIs is illustrated in Figure 1.

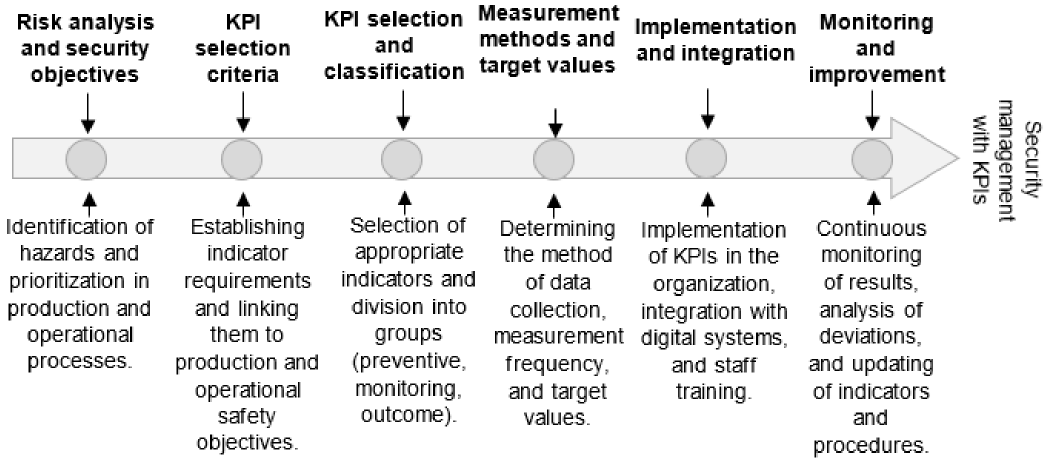

Fig. 1. Generalized model for selecting and managing production and operational safety with KPIs

The process of selecting, implementing, and managing production and operational safety using KPIs in manufacturing companies requires a structured approach. First, manufacturing processes are analyzed and risk areas are identified, which allows production and operational safety objectives to be defined. Next, the criteria for selecting indicators are defined so that they are measurable, relevant to the processes, and based on available data. The selected KPIs are classified into groups, which facilitates the assessment of preventive measures, ongoing monitoring, and the effects of the safety system.

The next steps include developing measurement methods, setting target values, and integrating KPIs with digital systems typical for Industry 4.0, which enables automatic data collection and analysis. After implementing the indicators in management structures, it is necessary to prepare personnel and adjust procedures to ensure proper use of the model. The system requires constant monitoring and interpretation of results, which allows for quick identification of deviations and corrective action. Regular verification of KPI effectiveness and updates ensure that the model remains useful and adapted to changing production conditions.

3. RESULTS

The model and its assumptions were verified at an aluminum industry company in south-eastern Poland. The company manufactures light metal alloy products for sectors such as energy, robotics, railways, mechanical engineering, engine technology, and aviation. The research was conducted in the first and second quarters of 2025.

The research included meetings with the company's management staff. Its purpose was to identify available information, safety indicators used, and to gather information about stakeholders and their expectations. During the discussions, the company's level of adaptation to the Industry 4.0 concept was also discussed. Particular attention was paid to the degree of process digitalisation, the monitoring technologies used, and the organisation's readiness to implement data-driven solutions.

Based on the results of these meetings, a survey questionnaire was developed, which was the main research tool. The questionnaire included a set of potential KPIs assigned to relevant safety areas and questions about the usefulness of the indicators and the possibility of their implementation in the production environment. The following criteria were used to select respondents: several years of experience in managerial positions, direct supervision of operational or safety processes, and knowledge of applicable procedures and reporting systems. Participants were selected in close cooperation with the CEO and HR manager, which ensured the participation of individuals with the appropriate knowledge and skills.

The selection of KPIs was supplemented by surveys. Participants rated individual indicators on a five-point scale, where 1 meant the lowest and 5 meant the highest significance. Of the 60 forms, 59 were complete, confirming the high level of commitment of the management staff. The results obtained were ranked and analysed in accordance with the adopted assessment method. The first stage involved a quantitative analysis (taking into account average ratings and standard deviation), which allowed the significance and consensus in the ratings to be determined. The second stage involved qualitative validation. The selected KPIs were re-evaluated in terms of their adequacy, operational usefulness and compliance with the company's strategic objectives.

The structured process of KPI selection and evaluation allowed us to identify the indicators that best correspond to the real needs of the company and the conditions of its operation. The developed and selected set of key performance indicators for production safety is presented in Table 1. KPIs were divided into preventive, monitoring, and result indicators, and their characteristics were presented.

Table 1
Characteristics of KPIs related to production safety

KPI type	KPI name	Target value	Purpose/ interpretation
Preventive	Health and safety training completion rate $$W1 = \frac{L_s}{L_{ws}} \cdot 100\%$$ where: L_s - number of employees after training; L_{ws} - number of employees requiring training	≥ 98%	Assessment of the degree of staff preparedness for safe work
	Machine safety inspection completion rate $$W2 = \frac{P_e}{P_p} \cdot 100\%$$ where: P_e - number of inspections performed; P_p - number of planned reviews	100%	Determines the level of implementation of preventive measures concerning the technical condition
Monitoring	Frequency of near misses $$W3 = \frac{Z_n}{T}$$ where: Z_n - number of reported near miss incidents; T - reporting period	≥ 5 reports/ month (expected high detection rate)	Indicates the level of operational risk and reporting culture
	Percentage of unplanned stops for safety reasons $$W4 = \frac{Z_B}{Z_t} \cdot 100\%$$ where: Z_B - detentions due to security violations; Z_t - all unplanned stops	≤ 10%	Determines the impact of threats on production continuity
Result	Production loss rate resulting from health and safety incidents $$W5 = \frac{S_B}{P} \cdot 100\%$$ where: S_B – production losses (e.g., quantitative or temporal); P - total production during the period	≤ 0,5%	Assesses the real impact of risks on production results
	Safety-related major machine failure rate $$W6 = \frac{A_B}{A_t} \cdot 100\%$$ where:	≤ 5%	Determines the proportion of security incidents in the total number of

	A_B - number of machine failures resulting from safety violations or inadequate safety measures; A_t - total number of failures in the analyzed period		machine failures; a high value suggests deficiencies in procedures, supervision, or technical safeguards.

Source: own work

The presented KPIs cover the full spectrum of production safety management, including preventive measures, ongoing risk monitoring, and incident impact assessment. Their selection allows for assessing the maturity of the organization in terms of prevention, controlling the stability of processes, and measuring the real impact of hazardous events on production operations.
The study also proposed KPIs for operational safety (Table 2).

Table 2
Characteristics of KPIs related to operational safety

KPI type	KPI name	Target value	Purpose/ interpretation
Preventive	Indicator of compliance of operating procedures with safety requirements $$W7 = \frac{P_r}{P_t} \cdot 100\%$$ where: P_r - number of procedures updated for security purposes; P_t - number of all surgical procedures	≥ 95%	Assessment of the degree of formal preparation of operational activities for safe implementation
	Indicator of corrective actions implemented following operational audits $$W8 = \frac{D_w}{D_p} \cdot 100\%$$ where: D_w - number of actions implemented; D_p - number of planned activities	≥ 90%	Demonstrates the effectiveness of the operational safety management system
Monitoring	Safety-related operational deviation indicator $$W9 = \frac{O_B}{T} \cdot 100\%$$ where: O_B - number of registered deviations affecting safety; T - reporting period	downward trend	Enables ongoing monitoring of operational risk and detection of process weaknesses
	Non-compliance rate in the area of operational safety $$W10 = \frac{N_B}{N_t} \cdot 100\%$$ where: N_B - safety non-conformities; N_t - total operational non-compliance	≤ 10%	Defines the share of security issues in total operational non-compliance
Result	Operational incident rate with an impact on safety	≤ 5%	Measures how often operational incidents

	$$W11 = \frac{I_B}{I_t} \cdot 100\%$$ where: I_B - incidents classified as critical to safety; I_t - all operational incidents		turn into safety-related events
	Operational downtime rate caused by security breaches $$W12 = \frac{T_B}{I_t}$$ where: T_β - downtime caused by security breaches; T_o - total operation time	≤ 1%	Measures the impact of security issues on the effectiveness of operational activities

Source: own work

The KPIs presented in Table 2 enable a comprehensive assessment of risk management in the operating environment. Preventive indicators allow for the assessment of the degree of preparedness of procedures and actions, monitoring indicators – current threat levels, and result indicators – the actual impact of incidents on the functioning of processes. The selected set of KPIs allows not only for effective risk management, but also for maintaining the stability of processes and protecting the organization's resources.
The target values for the KPIs in Tables 1 and 2 were determined based on several approaches. First, recommendations from senior management and safety specialists were used. The experts assessed realistic and operationally feasible indicator levels. Secondly, a comparative analysis of data from similar production plants was carried out. The aim was to ground the target values in practice and ensure their relevance to real operating conditions.
Each of the KPI groups indicated in Tables 1 and 2 allows for the assessment of the safety system from a different perspective. Production indicators focus on the protection of employees and equipment and the minimization of accidents in manufacturing processes, while operational indicators focus on process stability, procedural compliance, and limiting the impact of threats on the continuity of the organization's operations. In order to fully understand the specifics of both groups and their practical application, it is important to identify the main similarities and differences between these groups of indicators (Table 3).

Table 3
Key similarities and differences between production and operational safety indicators

Category	**Production safety KPIs**	**Operational safety KPIs**	**Comment / Difference**
	Main similarities		
Purpose of monitoring	Minimizing machine failures and production downtime	Minimizing accidents, incidents, and operational disruptions	Common goal: protecting resources (people, equipment, processes) and ensuring business continuity
Approach to risk	Assessing the risk of machine and process failures	Assessing the risk of accidents and procedural errors	Using risk analysis to prevent undesirable events
Prevention	Scheduled inspections, maintenance,	Health and safety training, procedure	Prevention and education are key in both areas

	machine operator training	audits, emergency drills	
Monitoring trends	Machine failure trends, reliability indicators	Accident trends, number of procedural violations	Identifying problem areas and improving safety systems
Main differences			
Scope	Protection of employees, machines, and production processes	Process stability, procedural compliance, and operational continuity	Production area – focus on physical security, operational area – focus on process and procedural security.
Purpose of preventive indicators	Prevention of accidents, machine and equipment failures	Ensuring procedural compliance and implementing corrective actions	Production prevention concerns technical condition and training; operational prevention concerns procedures and audits.
Purpose of monitoring indicators	Early detection of technical irregularities and potentially hazardous events	Monitoring operational deviations and procedural non-compliance	Production area – physical risk; operational area – procedural and organizational risk.
Purpose of outcome indicators	Assessment of actual accidents and incidents disrupting production	Assessment of the impact of incidents on process safety and operational downtime	Production area – impact on employees and machines; operations – impact on processes and organization
Type of data	Quantitative data from production, accident reports, reports of near misses	Procedural data, audits, operational incident records	Different data sources reflect the specific nature of the safety area
Perspective	Operational/ physical	Process/ organizational	Production safety measures the safety of workstations, while operational safety measures the efficiency and risk of processes

Source: own work

Safety indicators play a key role in monitoring the functioning of both production and operational processes. They allow for systematic tracking of undesirable events, support the analysis of their causes, and enable the implementation of corrective and preventive measures. Their use helps to raise safety standards, ensure continuity of operations, and improve the efficiency and reliability of processes.

Despite its usefulness, the proposed model has several limitations that should be taken into account in its practical application. These limitations include:

- dependence on data – the effectiveness of the model depends on the quality, timeliness and completeness of the data.
- neglect of human factors – the model focuses mainly on technical aspects and takes limited account of organisational culture, attitudes and employee awareness.

- the need for KPI calibration - general indicators need to be adapted to the specific nature of each company; failure to ensure calibration and adequacy of KPIs may distort the safety assessment.
- limited universality - the model is based on literature, surveys and expert consultations, and is therefore suitable for selected types of industrial enterprises; companies operating in other industries may require modification of KPIs.
- lack of long-term validation - a full assessment of effectiveness requires long-term use, especially with changing technology and processes.
- lack of predictability - the model is based on historical and current indicators, without taking into account predictive analytics or machine learning.

Although the model is not without its limitations, awareness of these limitations allows for better interpretation of the results obtained and increases the effectiveness of its use in practice.

4. CONCLUSION

In an era of increasing automation and digitization of production processes, issues related to production and operational safety are becoming crucial. This highlights the need to develop tools that enable the systematic assessment and optimization of performance indicators in modern manufacturing environments. The aim of the study was to create a model for identifying key performance indicators (KPIs) for production and operational safety in an automated manufacturing environment.

The verification of the proposed model confirmed its usefulness in identifying and selecting production and operational safety indicators. The presented model is a structured tool for identifying and evaluating KPIs used to measure the level of safety in manufacturing companies. The selected indicators are divided into three categories: preventive, monitoring and result-oriented. This division allows for a comprehensive safety assessment, covering both preventive measures, ongoing process monitoring and analysis of the effectiveness of implemented countermeasures, enabling a multifaceted and operationally useful analysis of the state of production safety.

The originality of the study lies in the development of a KPI model for safety in an automated production environment, which integrates preventive, monitoring and result indicators. The model combines a theoretical approach with practical survey research and expert consultations, takes into account the specific nature of Industry 4.0, and creates a basis for further predictive development using data analytics and machine learning.

The study can provide significant support to safety specialists, process engineers, and decision-makers responsible for quality and risk management in modern manufacturing plants, as it streamlines the decision-making process and promotes effective improvement and assurance of a high level of production and operational safety.

Future research directions will focus on extending the model with predictive elements based on data analytics and machine learning. In addition, there are plans to integrate information from intelligent monitoring systems, reflecting the growing role of cyber-physical systems in Industry 4.0.

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