A METHODOLOGY FOR MANAGING TECHNOLOGICAL RISKS IN HIGH-TECHNOLOGY FOOD PRODUCTION ENTERPRISES

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https://doi.org/10.5281/zenodo.22137471

Abstract. This thesis substantiated a methodology for managing technological risks in high-technology food production enterprises. The study examined the integration of HACCP principles, ISO 22000 and ISO 31000 standards, together with modern digital monitoring technologies. The proposed step-by-step framework improved the processes of risk identification, assessment, control, and continuous monitoring. The findings confirmed opportunities to enhance production stability, strengthen food safety, and improve the economic performance of food enterprises. The proposed methodology provided a practical scientific basis for effective technological risk management.

Keywords: technological risk, food safety, HACCP, ISO 22000, ISO 31000, risk management, digital monitoring.

Over the past decade the high-technology segment of the food industry has become markedly more complex, driven by automated processing lines, in-line measurement devices and digital control architectures. Each production step now operates as an interdependent assembly of technical, biological and informational components, and the notion of risk has correspondingly moved beyond its traditional sanitary boundaries to become a category that applies to the entire life cycle of the technological system. According to the World Health Organization data updated on 4 June 2026, unsafe food is associated with 866 million cases of illness annually, with 1.52 million attributable deaths, while the global productivity and medical cost burden is estimated at US$ 310 billion [1]. A burden of this magnitude elevates technological risk management from an auxiliary compliance exercise to a system-forming function of enterprise economics.

The theoretical core of contemporary risk governance rests on a preventive paradigm. The General Principles of Food Hygiene of the Codex Alimentarius Commission establish that hazards must be constrained within the process at critical control points rather than detected through end-product testing; in the revision adopted in 2020 the HACCP system was relocated from an annex into the main body of the code, which consolidated its status as a universal methodological instrument [2]. This position permits risk to be interpreted not as a stochastic event but as an identifiable and governable state of the process.

At the level of the individual enterprise, the organisational mechanism is formalised by ISO 22000:2018. The standard integrates HACCP principles and the application steps developed by the Codex Alimentarius Commission into a single management system that encompasses interactive communication, system management and prerequisite programmes [3]. Its second edition treats the handling of risks associated with organisational objectives as an explicit requirement, thereby situating product safety within the domain of strategic management rather than confining it to operational hygiene.

At the level of general risk theory, ISO 31000:2018 provides the supporting frame. It defines risk as the effect of uncertainty on objectives, proposes a triad of principles, framework and process, and retains the status of generic guidance rather than a certifiable specification [4]. Applied to food manufacturing, this model connects sector-specific safety requirements with the enterprise-wide governance architecture in which investment, maintenance and capacity decisions are taken.

The national institutional foundation has been reinforced consistently in recent years. The Law of the Republic of Uzbekistan "On Food Safety" No. ZRU-1023 of 3 February 2025 delimited the competences of state administration bodies, specified the rights and obligations of economic entities, and introduced a procedure for maintaining a national food safety database [5]. The adopted instrument created a firm legal basis for aligning the internationally established preventive control model with the national regulatory system.

Studies concerned with the maturation of national control systems have treated HACCP implementation as a matter of public policy rather than of firm-level discretion. Research summarising the Chinese experience established that the diversification of processing methods and the lengthening of trade chains make rigorous in-process hazard identification and evaluation decisive, and identified priority directions for further refinement of the system [7].

The integration of digital technologies into risk governance has formed a distinct research field. Work on the influence of big data on dynamic food safety risk management showed that sensor-based surveillance and analytical platforms allow the preventive approach to be coupled with decision-making in real time [8]. A study that tested a modified FMEA model on a yoghurt-filling system in an Industry 4.0 environment extended the conventional three-factor rating with a dependency factor, thereby improving the discriminatory power of the assessment for interconnected components [9]. A comprehensive survey of predictive maintenance provided a contemporary taxonomy of planning models and machine learning techniques used to anticipate equipment failure before it propagates into product loss [10].

Traceability has evolved into a separate line of enquiry. A systematic review of blockchain-based traceability frameworks covered the substantial body of publications accumulated since 2016 and established that immutability and transparency strengthen control over the supply chain [11]. A review devoted to agri-food chains identified practical routes for overcoming the information loss and tampering risks inherent in centralised traceability architectures [12].

The study is theoretical and analytical in character and follows a three-stage logic. The first stage applied comparative-institutional analysis to international standards and national normative acts: the Codex principles [2], the requirements of ISO 22000:2018 [3], the guidance of ISO 31000:2018 [4] and the provisions of Law No. ZRU-1023 [5] were compared with respect to their object of governance, control mechanism and verification procedure. The second stage employed content analysis of open-access scientific publications in order to construct a taxonomy of risk assessment instruments. The third stage synthesised the findings into a single staged model.

Sources were admitted under strict criteria: the publication had to possess a verifiable digital identifier or stable address, be available under open-access conditions, and originate either from an international organisation or from a peer-reviewed journal. Quantitative indicators were extracted exclusively from primary documents; estimated or secondary figures were excluded from the evidentiary base.

The quantitative core of the framework is the risk priority number. In its classical form it is obtained as the product of severity, occurrence and detection ratings [6]:

$$RPN = S \times O \times D, \quad (1)$$

where S denotes the severity of the consequence, O the probability of occurrence and D the difficulty of detection, each rated on a bounded ordinal scale. For automated lines operating in an Industry 4.0 environment the expression is extended by a dependency factor that reflects the degree to which a failure propagates across interconnected components [9]:

$$RPN^* = S \times O \times D \times Dp. \quad (2)$$

Expression (2) operationalises the risk analysis and risk evaluation phases prescribed by ISO 31000:2018 and converts them into a measurable enterprise-level instrument [4]. The generalised structure of the resulting framework is presented in Figure 1.

Comparative analysis established that the governing instruments stand in a hierarchical and mutually reinforcing relation. The Codex code fixes the principle of constraining hazards inside the process [2]; ISO 22000:2018 converts that principle into an operating management system with defined responsibilities and documentation [3]; ISO 31000:2018 supplies the general decision logic through which residual risk is weighed against objectives [4]. National legislation consolidates the three layers institutionally through state supervision and an information base [5]. The coherence of these layers is what permits technological risk governance to be constructed as an integral system rather than as a set of parallel compliance routines. The model comprises four stages. At the identification stage, hazard sources are registered for every operation of the technological route, which yields the input set for subsequent evaluation. At the assessment stage the risk priority number is computed according to expressions (1) and (2), and critical control points are separated from operations manageable through prerequisite programmes [6]. At the treatment stage a combined set of technical, organisational and digital measures is applied, including predictive maintenance algorithms [10] and traceability platforms [11]. The monitoring stage verifies the outcomes and, through the feedback loop, triggers revision of critical limits whenever process data indicate drift. The closed character of the cycle distinguishes the proposed framework from linear inspection schemes, since each iteration updates the parameters of the preceding stage.

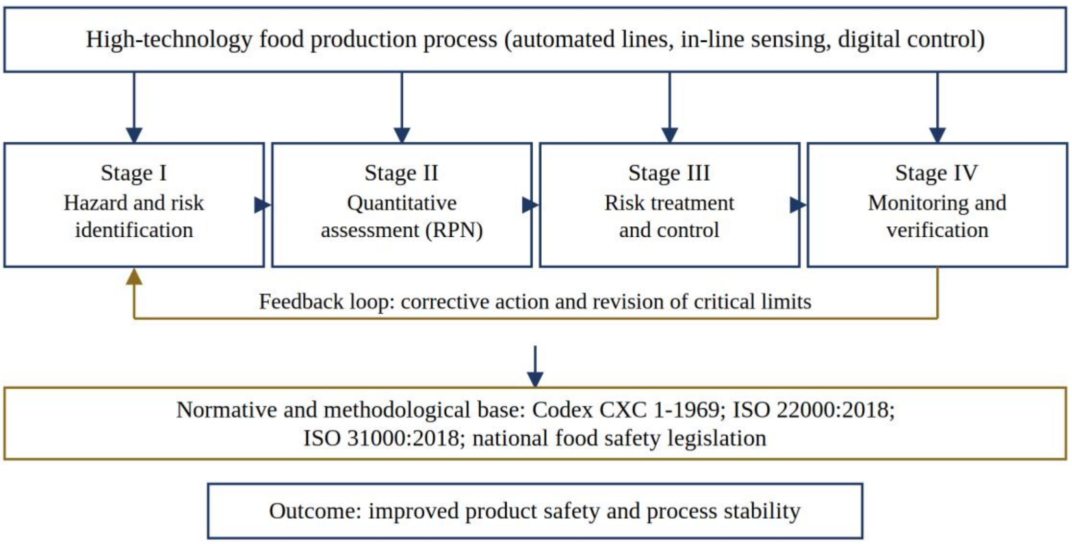

Figure 1. A staged model of technological risk management in a high-technology food production enterprise[1]

Risk categories, the corresponding governance instruments and their documentary basis are systematised in Table 1.

Table 1

Categories of technological risk in a high-technology food enterprise and the corresponding governance instruments[2]

Risk category	Domain of manifestation	Governance instrument	Source
Biological and microbiological risk	Raw material intake, thermal treatment, packaging	Critical control points, good hygiene practices, time and temperature control	[2]
Systemic and organisational risk	Management processes, documentation, allocation of responsibility	Food safety management system and prerequisite programmes	[3]
Strategic uncertainty risk	Attainment of objectives, resource allocation, decision-making	Risk governance based on the principles-framework-process triad	[4]
Regulatory compliance risk	State supervision, product circulation, information base	Adherence to statutory requirements and maintenance of the food safety database	[5]
Process failure risk	Sequence of technological operations, intermediate control	Risk priority ranking through FMEA, HAZOP, Ishikawa and Pareto analysis	[6]
Equipment and mechanical risk	Automated filling and packaging lines	FMEA model extended by an inter-component dependency factor	[9]

[1] Source: compiled by the author on the basis of [2], [3], [4] and [5].
[2] Source: compiled by the author on the basis of [2], [3], [4], [5], [6], [9], [10] and [11].

Downtime and interruption risk	Continuous production cycle, maintenance regime	Predictive maintenance driven by machine learning algorithms	[10]
Traceability risk	Supply chain, batch identification	Blockchain-based traceability and data integrity verification	[11]

The content of Table 1 reveals a property that is central to the argument: although the listed risk categories differ in physical nature, regulatory anchoring and time horizon, each of them passes through an identical governance sequence of identification, measurement, treatment and surveillance. This structural homogeneity supplies the theoretical justification for constructing one methodology instead of maintaining parallel systems for food safety and asset reliability.

The practical efficacy of the proposed framework is supported by results reported in open sources. A study conducted at a meat processing enterprise in Semey recorded that, six months after a HACCP plan had been implemented in accordance with ISO 22000:2018, the coliform count of the tested product fell from 4.4 MPN/g to 1.8 MPN/g, a statistically significant reduction [13]. A further study carried out in an ecologically compromised territory demonstrated that a HACCP plan functions as an effective instrument for controlling heavy metals, radionuclides and pesticide residues [14]. Both results evidence a measurable and favourable effect of standardised control systems on product quality parameters, which is precisely the outcome the cycle in Figure 1 is designed to reproduce.

From an economic standpoint, the estimation of annual global losses associated with unsafe food at US$ 310 billion [1] indicates a high return potential for funds committed to preventive control. At enterprise level this return materialises through three channels: a reduction in unplanned interruptions, secured by predictive maintenance of critical assets [10]; a decline in the volume of rejected output, achieved by narrowing critical limits at the points identified in the assessment stage [6]; and a strengthening of product reliability, which supports market access and contractual standing [12]. The framework consequently operates simultaneously as a safety instrument and as an instrument of cost management.

The study established an integral methodological framework for managing technological risks in high-technology food production enterprises. The framework rests on the coherent combination of international hygiene principles, management system standards, generic risk guidance and national legislative norms, and it treats technological risk as a governable state of the production process rather than as an external contingency.

First, enterprises are advised to formalise risk governance as a closed cycle of identification, quantitative assessment, treatment and monitoring, since such a structure secures the internal consistency of individual control measures and provides an audit trail aligned with recognised guidance [4].

Second, the procedure for computing the risk priority number should be fixed in internal methodological documentation, and for automated lines the inter-component dependency factor should be introduced as an additional criterion in order to improve the accuracy of ranking [9].

Third, the deployment of condition monitoring sensors together with predictive maintenance algorithms strengthens production stability by lowering the probability of unplanned stoppages and by converting corrective maintenance expenditure into planned expenditure [10].

Fourth, the use of digital solutions that guarantee data integrity in batch identification reinforces control over the supply chain and shortens the response time required in the event of a product withdrawal [11].

Fifth, systematic alignment of internal enterprise documentation with national statutory requirements, together with a defined procedure for interacting with the national food safety database, secures institutional conformity and reduces regulatory exposure [5].

The proposed framework may serve as a theoretical basis for sectoral research and, at a subsequent stage, as an object of empirical verification using data from individual enterprises. In implementation, the step-by-step handbook prepared jointly by international organisations offers a suitable reference document for organisational preparation [15].

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