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DEVELOPING THE BASIC CORE OF THE FOOD QUALITY AND SAFETY ASSURANCE SUBSYSTEM

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Abstract. *Contemporary challenges facing food manufacturing are shaped by the synergistic impact of multiple factors. Most significant among these is continuous technological advancement, unfolding within the context of supply chain globalization and increasingly complex value networks. These factors, compounded by the impact of significant socio-economic disruptions, have diminished the efficacy of traditional approaches to quality and safety assurance for processes and products in the food industry. Consequently, there is an imperative to refine these approaches to enhance their applicability within modern production environments, which are characterized by attributes such as modularity, technological sophistication, an extensive product range, and a high degree of product customization. The objective of this study was to establish the foundational core of manufacturing quality assurance for application within the production environments of modern food enterprises. This core constitutes a homologous, transversal, and additive subsystem that shapes the resultant developmental vector through functional integration into the production system, taking into account the interdisciplinary nature of contemporary complex value networks and stakeholder satisfaction. The study employed lexico-semantic alignment of international interdisciplinary normative documents and contemporary scientific models of quality control subsystems, alongside IDEF0 notation for systemic interconnections and ontological modeling. Based on the results, 10 foundational components were identified, comprising 102 structural and functional elements ensuring the systemic role of these components, and 6 types of interconnections, which collectively constituted the core architecture of the quality assurance subsystem. The proposed architecture is designed to meet contemporary requirements and optimize processes such as integration, monitoring, and regulation across all stages of the value chain through the establishment of a comprehensive technological infrastructure.*

Keywords: quality, ISO, HACCP, grain, food technology, IDEF0 notation, graph theory.

Introduction

Quality assurance is a paramount component of food manufacturing, serving as the foundation for operational efficiency, a safeguard for the quality and safety of the end product, and a prerequisite for stakeholder satisfaction. The concept of quality has undergone significant transformations, having originated as the ex-post inspection of end products involving the rejection of non-conforming outputs (Azamfirei, 2024). The approach to quality control has evolved in close tandem with scientific and technological advancement and the evolution of manufacturing paradigms, unfolding within the context of shifting socio-economic conditions. Gradually, the inspection-based approach was augmented by concepts of proactive control, process standardization, statistical process control, and the transition towards cyber-physical systems (Groumpos, 2021; Liu, 2023; Varshney, 2024). Today, quality is conceptualized as the capacity of a manufacturing system to consistently and predictably replicate desired outcomes within volatile environments and dynamic contexts, while accounting for the challenges of sustainability and public perception.

In the context of globalized supply and value chains, quality acquires new dimensions due to product diversification, which can be broadly categorized into informational, tangible, and service-oriented components. This categorization is driven by the distinct requirements and quality criteria inherent to each specific category, thereby complicating the unification of approaches and the standardization of requirements. Modern food manufacturing systems are characterized by a complex, multi-layered structure, wherein the final product emerges as an integrated synthesis of these categories, entailing the simultaneous generation of data flows, physical goods, and accompanying services (Lin, 2024). This multi-product paradigm implies that any defect, irrespective of its origin within the global chain, exerts an immediate and direct impact on the overall quality and the end consumer, who perceives the final product as a unified value proposition. It is precisely this interdependence that necessitates the implementation of combined systemic and process-oriented quality control across the entire span of the chain (Dewi, 2022).

The escalation of technological complexity, coupled with heightened demands for safety, environmental sustainability, and production stability, necessitates real-time control. This imperative is of paramount importance to the food industry due to a distinct set of characteristics that significantly differentiate it from other sectors. A primary differentiator is the pronounced vulnerability and instability of the physicochemical and biological properties inherent to food products throughout manufacturing, storage, transportation, and distribution (Khalid, 2024). Furthermore, the multi-component architecture of food systems necessitates a comprehensive approach to evaluating the interplay among ingredients, processing methodologies, and environmental conditions. Safety occupies a pivotal role in food manufacturing, serving as a critical factor and an attribute inextricably linked to quality (Hu, 2022). Food safety cannot be examined in isolation, as it is integrated into all facets of control, encompassing risk management, regulatory compliance, and the fulfillment of stakeholder requirements. Consequently, quality and safety in the food industry constitute a substantive and methodological unity. Finally, food products carry substantial socio-cultural significance. Their perception, evaluation, and consumption are intimately tied to cultural practices, traditions, religious beliefs, and individual preferences; this necessitates acute sensitivity to intangible factors when developing quality standards and formulating market positioning strategies (Rai, 2023). Ultimately, the multidimensional nature of food products engenders a complex and dynamic landscape for quality and safety assurance mechanisms.

The confluence of these challenges creates an environment wherein traditional approaches to food quality assurance are reaching the limits of their efficacy, as a strictly prescriptive approach cannot accommodate the vast array of quality and safety factor combinations present in the modern food industry. This, in turn, leads to a dilution of requirement specificity and an escalation of subjectivity during their implementation. Consequently, there is an evident imperative for a novel methodology that integrates flexibility, adaptability, a risk-based approach, and systemic responsiveness to external environmental shifts. Absent such a paradigm shift, quality assurance risks degenerating into a mere formalistic tool, devoid of the capacity to guarantee genuine reliability, stability, and consumer value within the contemporary economic landscape.

One viable strategy to address the crisis of the prescriptive approach is the development of a foundational model for a manufacturing quality assurance subsystem, grounded in the universal properties of production systems. Given the complex contemporary context and the broad spectrum of stakeholders imposing requirements on the food industry, an interdisciplinary approach is critical. Such an approach must accommodate the multi-product paradigm, customization, and risk-based methodologies as primary driving factors, thereby facilitating the development of a balanced subsystem capable of adaptation and integration into any manufacturing environment, irrespective of its scale, product typology, or technological specificity. The implementation of this model has the potential to ensure operational transparency, compliance with international standards, and the sustainable development of enterprises amidst a highly dynamic environment.

Literature Review

The contemporary constellation of challenges confronting food manufacturing in achieving the requisite level of quality for both production processes and their outcomes engenders a critical need for relevant solutions and stimulates the emergence of novel manufacturing quality assurance models. These models embody diverse approaches and encompass a substantial array of value chain components (de Giovanni, 2024). Nevertheless, a considerable proportion of these models remain narrowly focused on isolated aspects of manufacturing system operations, thereby leaving unaddressed the critical shortage of integrated models capable of coalescing all these dimensions into a unified framework.

One approach to addressing this problem involves the re-evaluation of international normative documents that regulate requirements for manufacturing quality assurance. A preeminent example is the ISO 9001 standard. Its architecture is predicated on general principles, which facilitates the harmonization of requirements across diverse sectors; however, to achieve this, it operates with high-level abstractions. Consequently, this necessitates substantial detailing and adaptation during implementation within specific manufacturing environments, particularly in the context of digital transformation (Duong, 2024). More industry-specific standards, such as ISO 22000, ISO 17025, and ISO 10004, among others, concretize the overarching principles of ISO 9001, focusing them down to the level of specific operational procedures and measurable criteria. Accordingly, the creation of a comprehensive approach requires the formulation and maintenance of an extensive repository of industry-specific normative documents, which allows for the accommodation of all value chain components relative to the particularities of each individual manufacturing process and product. In this context, a problem arises due to the absence of robust algorithms for their unified integration, taking into account the characteristics of modern agile manufacturing, multi-component products, and synergistic effects.

In parallel, the scientific approach to developing manufacturing quality assurance models continues to evolve. A contemporary example of this approach is a model that conceptualizes the manufacturing enterprise as a system of systems (SoS), encompassing internal resources, the external environment, decision-making mechanisms, and strategic objectives, the interplay of which dictates operational efficiency (Fuertes, 2020). Another variant involves models that focus on the nexus of production, maintenance, and quality control processes. These models are predicated on the tight interrelationship among these functions, accounting for the impact of equipment degradation, failure probability, inspection efficacy, and rework cycles on final product quality (Bouabid, 2024; Lu, 2024). They entail the simultaneous optimization of production volumes, maintenance scheduling, and inspection frequency, thereby facilitating cost minimization and quality stabilization. Furthermore, certain models emphasize the integration of diverse forms of capital including human, physical, and natural capital across operational, organizational, and strategic tiers (Misnan, 2022; Williams, 2022). This necessitates the decomposition of the manufacturing environment into interconnected substructures, each possessing its own objective, boundaries, functions, and internal logic. A distinct subset of models is anchored in the value chain concept, which spans physical production processes as well as digital activities, services, and knowledge management (Acquaye, 2023; Knez, 2021). Such models accommodate both tangible and intangible aspects, enabling the encompassment of a broader spectrum of contemporary manufacturing practices. In a related vein, manufacturing is occasionally analyzed as a globally organized process involving multiple actors, territorial disparities, institutional governance mechanisms, and the dynamics of inter-systemic interaction (Kano, 2020). Researchers underscore role specialization, regional coordination, and logistics, which are critical for transnational manufacturing operations. Distinct approaches are also emerging within the framework of digital transformation, particularly concerning small and medium-sized enterprises (SMEs) (Cruz, 2019). Within this trajectory, several clusters are identified that encompass key manufacturing elements, enabling the creation of adaptive systems that are responsive to volatile market conditions and oriented toward product individualization (Schreiber, 2022; Zurn, 2024). Moreover, modern architectures for cyber-physical production systems propose multi-layered models comprising physical, coordination, digital logic, and management layers, wherein each functional unit executes a specific operation on inputs to generate outputs in the form of decisions or services. This architecture ensures end-to-end traceability, feedback loops, and adaptive planning.

Consequently, a substantial corpus of diverse models has been proposed by researchers to date, predicated upon various conceptual dimensions of quality, characteristics of manufacturing processes, and stages of value creation. Within the context of the food industry, these models encompass a broad spectrum of determinants that influence the quality of both the manufacturing process and the final product. Nevertheless, they address only isolated components of a complex and multifaceted system, exhibiting a pronounced deficit in universality and integrative potential when confronted with the heterogeneity of modern enterprises, technological diversity, and the globalization of supply chains.

Among the models proposed in recent years, there exist both conceptual alignments and substantial divergences. A common denominator is the drive toward the integration of resources, processes, and objectives, coupled with the utilization of multi-tiered structures and an endeavor to encapsulate the adaptive nature of the manufacturing system. Conversely, divergences manifest in the level of abstraction, focal areas, the presence or absence of feedback loops, and the degree of formalization. The majority of these models remain industry-specific or fail to account for the pronounced heterogeneity of manufacturing paradigms, product types, and their intersections. This recurrently leads to fragmentation, thereby constraining their scope of applicability and interoperability. Consequently, this precludes the establishment of a unified manufacturing quality control system suitable for deployment within complex production environments that are configured on the basis of shared resources and functional alignment, underpinned by reliable information flows (Sousa, 2021; Vieira, 2021).

The unification of manufacturing quality assurance approaches represents a pivotal step in overcoming the fragmentation and incompatibility prevalent among the multitude of industry-specific standards and models currently deployed within manufacturing systems. Of particular significance in this endeavor is the establishment of an end-to-end logic that encompasses the continuum of phases from value stream mapping and rational resource allocation to the monitoring and management of process variability (Lin, 2024). Empirical studies corroborate the efficacy of integrated models that coalesce production, maintenance, and quality control into a unified functional system; such integration facilitates simultaneous cost reduction and the preservation of consistent quality levels amidst highly dynamic environments (Kusiak, 2022).

Theory of Systems, serving as the foundation for conceptual modeling, facilitates the conceptualization of manufacturing operations as a dynamic network of interacting subsystems subject to external and internal factors of variability. Within such a network, quality assurance does not function in isolation; rather, it is integrated into the manufacturing system, endowing it with emergent properties (Bobe, 2025). All typologies of manufacturing systems share fundamental attributes, including the presence of resource inputs, transformational processes, generated outputs, elemental interactions, systemic objectives, and the iterability of the production cycle (Romero, 2024). Consequently, the universalization of the 'manufacturing' concept as a fundamental entity constitutes the initial step, paving the way for the development of a foundational model oriented toward the structural and functional organization of the value creation process. This approach provides the requisite level of abstraction, enables the generalization of typological characteristics, and lays the groundwork for the subsequent structuring, modeling, and risk-based adaptation of the quality control system.

Against this backdrop, ontological modeling methodology emerges as one of the most viable analytical approaches. Ontologies facilitate the formalization of concepts, processes, and interconnections within manufacturing systems, irrespective of their industry-specific nature. Universal concepts such as "resource", "process", "product", "information", and "objects" provide a shared semantic framework and serve as the foundation for developing interoperable systems (Sapel, 2024). As formalized knowledge representations, ontologies enable the creation of structured conceptual hierarchies that encompass not merely physical manufacturing assets such as "equipment", "materials", and "tools" but also intangible entities, including "information flows", "decision-making rules", and "control parameters" in the context of food quality and safety, this implies that all facets of process evaluation, control, and improvement can be represented within an ontological environment via rigorously defined entities, relations, and logical rules. It is particularly noteworthy that the ontological approach permits the modeling of not only linear workflows but also decision-making logic, inter-stage dependencies, sequencing, modular alterations, and potential deviation scenarios within the framework of risk-based quality control. Because ontologies can be instantiated using empirical data, they retain adaptive capacity, sustain flexibility, and facilitate the creation of dynamic models that are responsive to fluctuating parameters within both internal and external environments (Sanfilippo, 2021). It is precisely these characteristics that ensure the universality and integration potential of the resulting model with digital systems for subsequent analysis a capability of paramount importance in the era of Industry 4.0 (Yang, 2023).

The subsequent augmentation of modeling and analytical capabilities utilizing graph structures enables the forecasting of secondary consequences, the identification of vulnerable systemic nodes, and the formulation of intervention scenarios. Consequently, quality assurance evolves into a dynamic process deeply rooted in the complex interplay of manifold components (Zhong, 2020). Thus, ontological modeling furnishes the analytical foundation for developing the foundational core of the manufacturing quality assurance subsystem model within the food industry. This core coalesces the prerequisites for structural transparency, adaptability to change, resilience against disruptions, and relevance to digital environments. The application of such a model facilitates systemic mapping and the management of its dynamics, the diagnosis of vulnerabilities, the simulation of decision outcomes, and the sustainment of holistic functionality amidst volatile conditions.

Materials and Methods

Materials of this study is 10 international standards that define the conceptual framework of quality and the requirements for quality and product safety management within an interdisciplinary context: ISO 9000:2015, ISO 9001:2015/Amd 1:2024, ISO 22000:2018/Amd 1:2024, ISO/IEC 17025:2017, ISO 15189:2022, ISO/IEC 25012:2008, ISO/IEC 25002:2024, ISO 14001:2015/Amd 1:2024, ISO 45001:2018/Amd 1:2024, and ISO 10004:2018. Furthermore, the analysis encompassed 28 contemporary models of manufacturing quality assurance systems introduced in scholarly publications between 2020 and 2025

The identification of components for the foundational model of the manufacturing quality assurance subsystem was conducted utilizing lexical and semantic comparison of the sources (Salloum, 2020), followed by the aggregation of functionally analogous categories (Zhang, 2024). This approach entailed the alignment of terms and structural elements contained within the sources to ascertain recurring equivalents, incorporating the recommendations stipulated in ISO/IEC 11179-1:2023. The analysis was executed according to the following algorithm: (1) lexical-semantic alignment of the terminological apparatus across documents, wherein the meanings of terms were compared and clustered into functional categories (e.g., "resources", "processes", "control", "risk management"), after which semantically equivalent terms recurring in three or more documents were incorporated into a candidate list; (2) lexical-semantic mapping of the titles and contents of structural components within the standards (sections, clauses, subclauses) and informational blocks within publications, during which sources were evaluated for lexical similarity in formulation and semantic functional correspondence, followed by the inclusion of blocks exhibiting analogous logical-functional roles that recurred in three or more sources into the candidate list; (3) aggregation of the candidate list into overarching categories predicated on functional affinity with respect to manufacturing quality assurance.

The identification of the structural-functional elements of the model's components was executed through the decomposition of the component lifecycle, which encompassed the following phases: (1) the identification and actualization of requirements imposed upon a specific component by international normative documents; (2) the attainment of compliance status for the component regarding the identified requirements; (3) the monitoring of the component's stability and functional conformity against the identified requirements; (4) the execution of corrective actions in the event of detected destabilization or non-conformity of the component with the identified requirements. In alignment with this cycle, categories of higher granularity were established, which are requisite for ensuring the component's structure-function as stipulated by international normative documents.

The identification of interconnection types among the model's components was executed through a logical-semantic analysis of the identified components and their structural and functional elements. During this procedure, a comprehensive IDEF0 notation for the components was formulated (Spanidis, 2022) predicated on the following criteria: the Input encompasses the operational requirements of the component; the Output embodies the outcome of fulfilling these requirements; the Control comprises regulatory factors governing the realization of the requirements; and the Mechanism constitutes the methods and resources deployed to achieve the requirements. In alignment with the formulated notation, the derivation of interconnection types was performed, corresponding to the control factors and mechanisms by which the component satisfies the stipulated requirements.

The identification of the input and output interfaces for the model's components was executed utilizing the IDEF0 notation of the identified components (Spanidis, 2022). This notation was formulated according to the following criteria: the Input comprises components that transmit resources and information, or dictate the function of the component under analysis; the Output encompasses components that receive resources and information, or are functionally dependent upon the component under analysis; the Control involves components that exert coordinative and managerial influences, or relay feedback to the component under analysis; and the Mechanism incorporates elements that determine the structure-functions of the component under analysis.

The categorization of interfaces into inputs and outputs was accomplished via the generation of a functionally-oriented graph, wherein each component was conceptualized as a node, and its interactions as directed edges between them (Xiangyu, 2021; Zhong, 2020), with the explicit exclusion of self-loops (self-interactions), as a component's influence upon itself does not generate novel systemic linkages. To construct the graph, a sequential pairwise comparison of the components was executed utilizing IDEF0 notation to ascertain whether one component serves as an origin of influence upon another and to delineate the nature of this influence. The mapping of interconnections among the system's components was conducted employing a "black box" methodology. This approach entails analyzing exclusively the input and output signals of each component without resolving its internal processes including signal transformation, substitution, or reactive modifications in the component's state given that these internal dynamics do not alter the presence of input and output interfaces.

To validate the logical architecture of the foundational quality model, an ontological approach was utilized. Specifically, the component and relationship model was instantiated as an ontology using the Web Ontology Language (OWL), formalized in the Turtle (*.ttl) syntax as 'source component – target component – relationship type' triples. Each identified system component was conceptualized as a subclass of a generalized overarching class, while the interdependencies among them were represented as pairs of object properties characterizing the input and output interfaces. Validation was executed employing the HermiT 1.4.3.456 semantic reasoner, integrated within the Protégé software environment. This procedure entailed a rigorous analysis to verify the absence of logical inconsistencies among object properties, the accurate execution of logical operations such as equivalence, disjunction, and intersection and the congruence of relationship types with the intrinsic nature of the components.

Results and Discussion

The comparison of interdisciplinary normative documents and contemporary models of quality control subsystems revealed the presence of shared categories inherent to any configuration of manufacturing activity. These categories were adopted as the minimal requisite components for value creation. They include: "Work environment and occupational safety", "Personnel", "Equipment", "Consumables", "Objects", "Methods and technologies", "Measurement uncertainty", "Risks and opportunities", "Information", and "Management". These components are categorized into three functional subgroups that are essential for executing manufacturing operations and that dictate the quality of the production outcome. These subgroups are represented by functions such as the operational execution of processes, infrastructure, and systemic management and development.

The "Work environment and occupational safety" component functions to ensure a stable, secure, and controlled space wherein manufacturing processes are executed. The "Personnel" component encompasses both operators and managerial staff, ensuring the execution of manufacturing functions through the activities of a qualified and competent workforce. The "Equipment" component provides the material foundation for executing manufacturing processes, serving as the bearer of the system's technological capacity. The "Consumables" component functions to supply the manufacturing process with single-use or reusable resources, which are deployed for a finite duration and are subject to replacement, disposal, or recycling, contingent upon the specific technological scenario. The "Objects" component represents the tangible bearers of manufacturing functions that act as the subjects of operational impact such as raw materials, intermediate goods, and the final manufactured product itself. The "Methods and technologies" component acts as the operational core of the manufacturing system, ensuring the execution of processes in accordance with established objectives, requirements, and quality criteria. The "Measurement uncertainty" component serves to ensure the validity and reliability of quantitative results derived from measurement procedures within the manufacturing process. The "Risks and opportunities" component fulfills a strategic function that directly impacts the achievement of the system's objectives. The "Information" component exercises a system-forming function, enabling the structured management of all data flows that constitute the foundation for decision-making, control, documentation, and inter-component interactions. Finally, the "Management" component serves as the integrative element of the system, providing strategic governance over all manufacturing components while sustaining their coherence, efficacy, and adaptive capacity.

The ten identified components constitute the minimal requisite universal set of entities, enabling the encompassment of key aspects of manufacturing activity from the operational execution of processes to infrastructure and the maintenance of systemic homeostasis. This architecture is oriented toward achieving the systemic objective, the primary facets of which are efficiency and productivity. Quality assurance, in turn, has as its primary objective the stability and quality of both the manufacturing processes and production outcomes. The integration of the quality assurance subsystem into the manufacturing system shapes the resultant developmental trajectory of the system, striking a balance between maximizing productivity and efficiency, and maximizing quality and stability. As a result of this integration, each component of the manufacturing system acquires emergent properties and functions designated to satisfy established internal and external requirements via the identification, attainment, and monitoring of quality and stability criteria. Consequently, the quality assurance subsystem is homologous to the manufacturing system (possessing an identical structure and components), transversal (the integration process is realized by embedding corresponding components within one another), and additive (the integration engenders supplementary functions and properties within the components of the manufacturing system).

Each identified component, in turn, constitutes a complex subsystem. Categories of higher granularity are expressed via structural and functional elements. In accordance with the systems approach, structure and function do not exist in isolation; rather, they exist in a state of mutual conditioning: function dictates the requisite structure, while structure establishes the conditions for functional execution. Consequently, these elements represent the decomposition of the component's primary function, reflecting its lifecycle and actualizing the function within specific spatial, technical, and organizational modalities. Furthermore, these elements govern the input and output interfaces requisite for the systemic interaction among all components.

Table 1 – Structural-functional elements of the identified components within the manufacturing quality assurance subsystem model

Name	Components	Count
"Work environment and occupational safety"	Sanitary conditions, technological conditions, confidentiality, engineering and technical infrastructure, external environment, internal environment, zoning, routing, decontamination, maintenance, contingency situations.	11
"Personnel"	Qualification, competence, impartiality, confidentiality, internship, certification, job descriptions, routing, stability.	9
"Equipment"	Technical characteristics, specifications, safety, compatibility, labeling, verification, calibration, inter-calibration interval, legal verification, stability, routing, maintenance, storage, instructions, operation.	15
"Consumables"	Technical characteristics, specifications, safety, compatibility, incoming control, registration, accounting, storage, stability, routing, instructions, operation, disposal.	13
"Objects"	Technical characteristics, specifications, safety, compatibility, incoming control, registration, accounting, storage, stability, routing, instructions, operation, disposal.	13
"Methods and technologies"	Technical characteristics, specifications, safety, compatibility, validation, verification, internal control, stability, external control, instructions, routing, operation.	12
"Measurement uncertainty"	Sources, evaluation, operation, review.	4
"Risks and opportunities"	Context, identification, evaluation, treatment, operation, review.	6
"Information"	Workflow, routing, information technologies, actualization, backup, archiving, confidentiality, protection.	8

Name	Components	Count
"Management"	Policies, objectives, planning, integration, resource allocation, communication, internal audit, analysis, non-conformity, corrective actions, changes.	11
Total		102

Consequently, the proposed structure facilitates a holistic approach to the analysis of manufacturing processes. It accounts for both the internal requirements of the enterprise to maintain homeostasis and the external challenges associated with regulatory compliance, consumer expectations, and scientific and technological progress.

Inter-component relationships play a key role in the system's operation, ensuring their synergistic interaction. Through the structured interplay of these components, the system acquires the properties requisite for implementing the strategic and tactical tasks of quality control at the current stage of manufacturing development. To identify the types of interconnections between components, a logical-functional IDEF0 analysis was applied, and a description for each component was formulated, as presented in Table 2.

Table 2 – IDEF0 composition of the components within the manufacturing quality assurance subsystem model

Name	Input	Output	Control	Mechanism
"Work environment and occupational safety"	Requirements, resources, workload	Controlled production space, control protocols	Normative documents, safety policies	Sensors, personnel
"Personnel"	Processes, rules, standards	Competent personnel, executed operations	Qualification requirements, regulations	Instructors, training programs, personnel
"Equipment"	Accuracy requirements, technical specifications	Stable operation, measurement data	Operating instructions, checklists	Engineers, equipment, maintenance
"Consumables"	Specifications, manufacturing needs	Ready for use Materials	Quality standards, procurement plans	Suppliers, control system
"Objects"	Materials, personnel, equipment	Production output	Object management procedures	Executive personnel, infrastructure
"Methods and technologies"	Technical assignment, product parameters	Described procedures, instructions	Methodologies, normative documents	Technologists, analysts, experts
"Measurement uncertainty"	Methods, measurements, standards	Estimated uncertainty, corrections	Accuracy requirements, metrology	Laboratories, analysis systems
"Risks and opportunities"	Context, analytics, incidents	Risk report, response plans	Normative documents, internal protocols	Analysts, consultants, IT systems
"Information"	Requirements, process data, control results	Information flows, messages	Communication regulations, information policy	IT systems, managers, personnel
"Management"	System requirements, inspection results	Plans, audit programs, reports, corrective actions	Internal policies, normative documents	Auditors, managers, management system

Based on the results of the IDEF0 notation development, 10 semantic formulas were formulated for each identified quality control component, followed by the identification of the corresponding relationship type. Accordingly, six types of interconnections were identified, as presented in Table 3.

The identified relationships are categorized into three complementary pairs. The "functional-feedback" pair implements the key components of system dynamics, encompassing task execution and adaptation to change. Together, they ensure a balance between operational stability and flexibility, which is critical for the functioning of complex systems. The "informational-material" pair reflects the exchange of resources between system components. These relationships form the basis for ensuring informational and material flows. The "managerial-coordinative" pair determines the organization of the system's work and forms a management structure that integrates strategic planning with process alignment in ongoing activities.

The analysis of the frequency distribution of connection types in the model revealed that informational connections are the most prevalent, accounting for 49.56% of the total interactions. This indicates the key role of data exchange in the quality assurance process. Informational connections determine the flow of data both within the manufacturing environment and in interaction with external factors, including legislative and international standards as well as stakeholders. Owing to this, the model can maintain universality by adapting to the specifics of different enterprises and manufacturing processes. Functional (21.24%) and material (10.62%) connections ensure the performance of the system's core tasks. They directly influence the feasibility of technological processes and the preservation of product properties. The group with limited frequency includes feedback (7.08%), managerial (8.85%), and coordinative (2.65%) connections, which perform supporting functions aimed at ensuring the system's adaptability and stability. Thus, the quality control system model is based on informational and functional connections, while other types of connections guarantee its flexibility, resilience, and adaptability.

Table 3 - Characteristics of the established relationship types within the architecture of the manufacturing quality assurance subsystem model

Link	Entity	Goal	Character	Result of interaction	Use
Functional	Ensure the performance of functions or the achievement of goals	Implementation of the core functions of the components	Direct interaction between components	Ensuring the component's functionality	Primary type of connection for operational functions and the path for requirement implementation
Informational	Ensure the exchange of data and knowledge	Informing and ensuring mutual understanding	Transmission of information without changing the state of components	Knowledge transfer for decision-making or actions	Decision-making support and transmission of requirements
Material	Physical or energy exchange between components	Ensuring material or energy needs	Physical or resource exchange	Meeting resource requirements	Ensuring the physical operation of the system and a means of fulfilling requirements
Managerial	Regulate component actions through control and management	Organization, regulation, and rule-setting	Hierarchical: from the governing to the governed component	Implementation of policies, procedures, and instructions	Organization and control of work and establishment of requirements
Feedback	Influence of component action results on their future behavior or other components	Stabilization or development of the system	Results of component actions influence their state	Action correction, system optimization	Ensuring stability, responding to deviations, and satisfying requirements
Coordinative	Coordinate actions between peer components for synchronization	Ensuring harmony of actions and resources	Peer-to-peer: horizontal interaction	Alignment of actions to achieve a common goal	Supporting coordinated interactions between components and meeting requirements

To determine the sources of influence and the directions of transfer for information, material resources, functional actions, management decisions, coordinative interactions, and feedback signals that constitute the unified interaction space of the quality control system, the six identified relationship types were categorized into inputs and outputs for each of the ten system components. Identifying input connections enables the identification of which components receive resources, information, or management decisions to implement their functions. The definition of output connections reflects the elements that produce results or exert influence on other components of the system.

Differentiating connections by their directionality enables the definition of roles for each component and the characterization of their input and output interaction interfaces within the network. Clear identification of these interfaces prevents conflicts and the duplication of functions, while facilitating the optimization of flows and influences aimed at adapting the system to changes in both internal and external environments.

As a result of the reasoning procedure using the HermiT logic module of the Protégé software, no logic violations or interface conflicts were detected. The consistency of the established classes and subclasses of components and structural-functional elements, the absence of contradictions between the defined model properties, the correctness of the use of constraints and logical operations, including equivalence, disjointness, and intersection, as well as the compliance of individual types with the constraints imposed on them by classes and properties, were confirmed.

Table 4 - Input connections to components (from horizontal to vertical)

Direction		To									
		I	II	III	IV	V	VI	VII	VIII	IX	X
From	I	-	Inf, Fun.	Inf, Fun.	Fun.	Fun.	Fun.	Fun.	Inf.	Inf.	Inf.
	II	Fee, Inf.	-	Fee, Mat, Fun.	Fee, Mat, Fun	Fee, Mat, Fun.	Fee.	Fee, Fun.	Fee.	Inf. Fun.	Fee, Inf, Fun.
	III	Inf.	Inf, Mat, Fun.	-	Inf, Mat.	Mat	Fun	Fun.	Inf.	Inf.	Inf.
	IV	Inf.	Inf, Mat, Fun.	Inf, Mat.	-	Inf Mat	Fun	Fun.	Inf.	Inf.	Inf.
	V	Inf.	Inf, Mat, Fun.	Inf, Mat.	Inf, Mat.	-	Fun	Fun.	Inf.	Inf.	Inf.
	VI	Inf.	Inf, Mat.	Inf.	Inf.	Inf	-	Inf.	Inf.	Inf.	Inf.
	VII	-	Inf.	-	-	-	Inf	-	Inf.	Fun.	Inf.
	VIII	Inf.	Inf.	Inf.	Inf.	Inf	Inf	Inf.	-	Fun.	Inf.
	IX	Inf.	Inf, Coo, Man, Fun.	Inf.	Inf.	Inf	-	-	Inf.	-	Man.
	X	Man.	Coo, Man.	Man.	Man.	Man.	Man.	Man.	Inf.	Man.	-

Notes: Fun - Functional; Inf - Informational; Mat - Material; Man - Managerial; Fee - Feedback; Coo - Coordinative.

Table 5 – Output connections from components (from vertical to horizontal)

Direction		From									
		I	II	III	IV	V	VI	VII	VIII	IX	X
To	I	-	Inf, Fee.	Inf.	Inf.	Inf.	Inf.	-	Inf.	Inf.	Man.
	II	Inf, Fun.	-	Inf, Mat, Fun.	Inf, Mat, Fun.	Inf, Mat, Fun.	Inf, Coo.	Inf.	Inf.	Inf, Coo, Man, Fun.	Coo, Man.
	III	Inf, Fun.	Fee, Mat, Fun.	-	Inf Mat	Inf, Mat.	Inf	-	Inf.	Inf.	Man.

Direction		From									
		I	II	III	IV	V	VI	VII	VIII	IX	X
	IV	Fun.	Fee, Mat, Fun.	Inf, Mat.	-	Inf, Mat.	Inf.	-	Inf.	Inf.	Man.
	V	Fun.	Fee, Mat, Fun.	Mat.	i Mat	-	Inf.	-	Inf.	Inf.	Man.
	VI	Fun.	Fee.	Fun.	Fun	Fun.	-	Inf.	Inf.	-	Man.
	VII	Fun.	Fee, Fun.	Fun.	Fun	Fun.	Inf.	-	Inf.	-	Man.
	VIII	Inf.	Fee.	Inf.	Inf.	Inf.	Inf.	Inf.	-	Inf.	Inf.
	IX	Inf.	Inf, Fun.	Inf.	Inf.	Inf.	Inf.	Fun.	Fun.	-	Man.
	X	Inf.	Fee.	Inf.	Inf.	Inf.	Inf.	Inf.	Inf.	Man.	-

Notes: Fun - Functional; Inf - Informational; Mat - Material; Man - Managerial; Fee - Feedback; Coo - Coordinative.

Based on the results of identifying the components of the base model of the manufacturing quality assurance subsystem, a graph has been formed with a set of vertices represented by components and edges represented by a set of input and output connections.

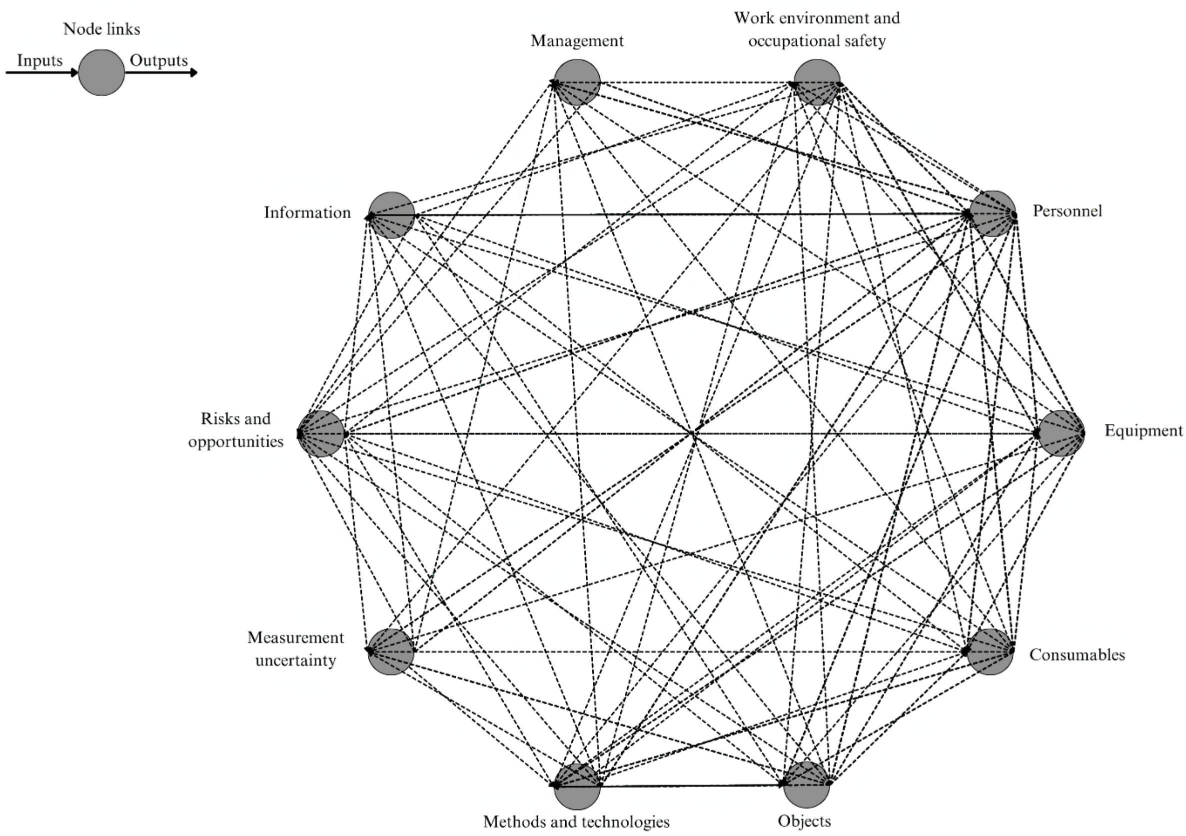
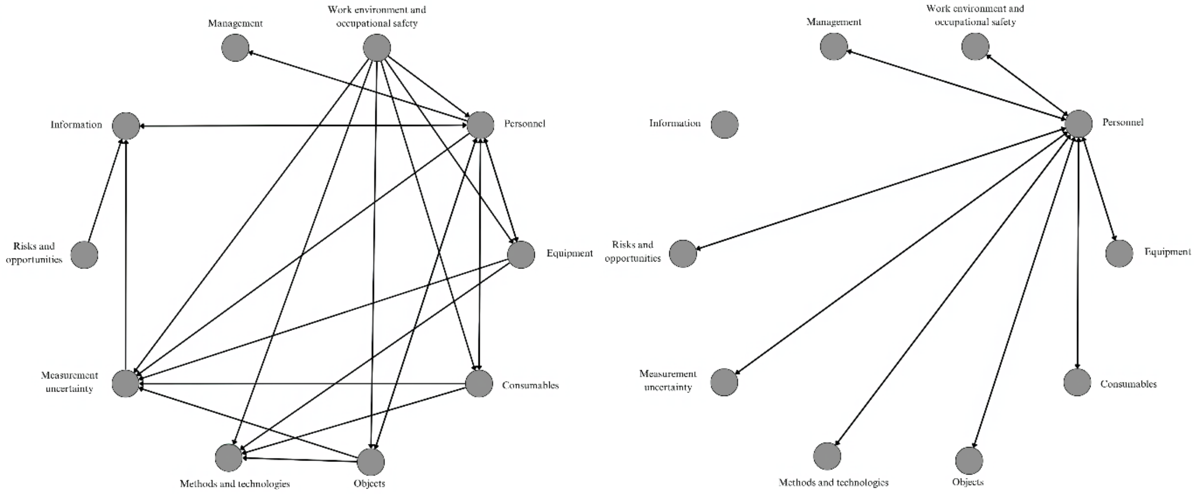


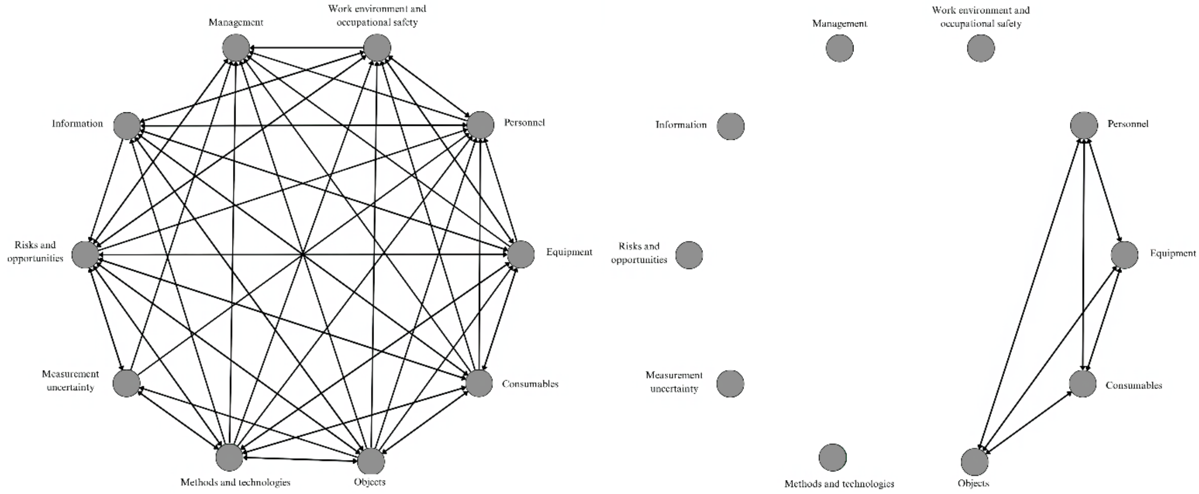
Figure 1 – General graph of the quality assurance subsystem model basecore

The formed graph is a directed, weighted network, where each node corresponds to one of the ten components of the quality assurance subsystem model, and the edges between them reflect the intensity of the influences of one component on another. The separation of its constituent connection types is presented in Figures 2-4.



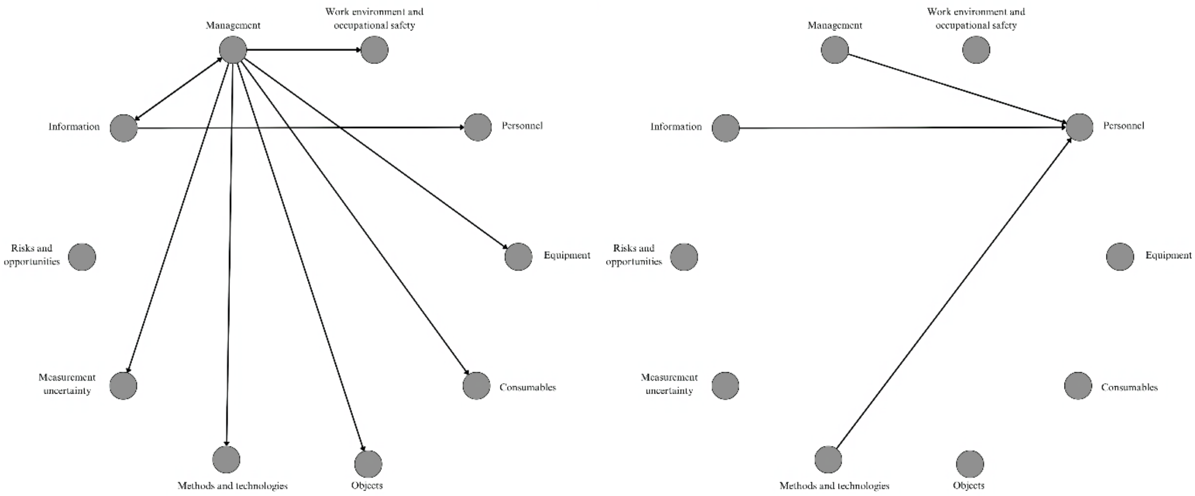
Functional links Feedback

Figure 2 – Graphs of input and output links of the "functional-feedback" pair



Information links Material links

Figure 3 – Graphs of input and output links of the "information-material" pair



Managerial links Coordination links

Figure 4 – Graphs of input and output links of the "managerial-coordination" pair

The presented graphs represent the core, depicted by the minimum necessary architecture of components and interconnections that establish the conditions for the production process and result to comply with interdisciplinary international requirements. This model is intended for further research into network characteristics to determine the potential for its application in ensuring quality throughout the entire value chain in the food industry.

Conclusions

Based on the research results, the core has been defined and the architecture of the base model for the production quality assurance subsystem has been formed. The capacity for integration into enterprises of various scales and focuses is achieved through the frequency distribution structure of connection types, where information interactions play a dominant role, accounting for 49.56% of the total number. Specifically, data exchange serves as a universal mechanism for synchronizing requirements, assessing risks, planning activities, and ensuring compliance with legislative and industry standards. Due to this design, the model is capable of adapting to various production environments, providing a foundation for effective integration into a wide range of manufacturing sectors.

The model is implemented through the formation of a directed network, which is a system with structurally organized components, clear functions, connections, and a common goal. Further study of the graph's network characteristics and its architectural topology will allow for the assessment of interconnection density, the identification of vulnerable nodes, and the determination of necessary measures for system integration. Graph optimization tools can be used to minimize control paths, reduce duplication of actions, and distribute the load within the quality system, which is especially important for small and medium-sized food enterprises with limited resources. Translating the ontological model into the domain of quantitative characteristics will also provide broad prospects for modeling system behavior under unstable conditions, encompassing both internal processes and external influences. In addition, the model's significant potential for use in machine learning and the integration of modern technologies should be highlighted, as it is of great importance for ensuring food safety in a globalized supply chain.

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РОЗРОБКА БАЗОВОГО ЯДРА ПІДСИСТЕМИ ЗАБЕЗПЕЧЕННЯ ЯКОСТІ ТА БЕЗПЕКИ ХАРЧОВИХ ПРОДУКТІВ

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Анотація. *Сучасні виклики, що стоять перед виробництвом харчових продуктів, формуються синергетичним впливом багатьох факторів. Найважливішим серед них є постійний технологічний прогрес, що розгортається в контексті глобалізації ланцюгів поставок та дедалі складніших мереж створення вартості. Ці фактори, що посилюються впливом значних соціально-економічних потрясінь, знизили ефективність традиційних підходів до забезпечення якості та безпеки процесів і продуктів у харчовій промисловості. Отже, існує необхідність удосконалення цих підходів для підвищення їхньої застосовності в сучасних виробничих середовищах, які характеризуються такими атрибутами, як модульність, технологічна складність, широкий асортимент продукції та високий ступінь кастомізації продукції. Метою цього дослідження було встановлення основоположного ядра забезпечення якості виробництва для застосування у виробничих середовищах сучасних харчових та зернопереробних підприємств. Це ядро являє собою гомологічну, трансверсальну та адитивну підсистему, яка формує результуючий вектор розвитку шляхом функціональної інтеграції у виробничу систему, враховуючи міждисциплінарний характер сучасних складних мереж створення цінності та задоволення зацікавлених сторін. У дослідженні використовувалося лексико-семантичне узгодження міжнародних міждисциплінарних нормативних документів та сучасних наукових моделей підсистем контролю якості, а також нотація IDEF0 для системних взаємозв'язків та онтологічного моделювання. На основі результатів було визначено 10 фундаментальних компонентів, що включають 102 структурні та функціональні елементи, що забезпечують системну роль цих компонентів, та 6 типів взаємозв'язків, які разом складають основну архітектуру підсистеми забезпечення якості. Запропонована архітектура розроблена для задоволення сучасних вимог та оптимізації таких процесів, як інтеграція, моніторинг та регулювання на всіх етапах ланцюжка створення цінності шляхом створення комплексної технологічної інфраструктури.*

Ключові слова: якість, ISO, HACCP, зерно, харчові технології, нотація IDEF0, теорія графів.

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