Research Article

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Real-Time Ammunition Case Quality Control System Design

Kerem Albayrak*[a], Adnan Akkurt[b]

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[a*] Gazi University, Technology Faculty, Dept. of Industrial Design Engineering 06560 - Ankara, Türkiye, Orcid: 0000-0001-9138-238X
[b] Gazi University, Technology Faculty, Dept. of Industrial Design Engineering 06560 - Ankara, Türkiye, Orcid: 0000-0002-0622-1352
*Corresponding author: kerem.albayrak@gazi.edu.tr

ABSTRACT

Keywords: Quality control automation, ammunition case inspection, image processing, computer vision in manufacturing, real-time defect detection

This study aims to develop an automation system designed to enhance the quality control processes of ammunition cases of various calibers using a systematic design approach. Traditional quality control methods in ammunition manufacturing largely depend on human factors, which carry a high potential for error and limit efficiency. The aimed system utilizes advanced image processing algorithms integrated with mechanical and electronic components to perform quality control tasks at high speeds with nearly perfect accuracy. This significantly reduces human error, aiming for a more consistent and reliable control process. The system developed through this research is expected to make significant contributions to sectors that require high precision and reliability, such as the defense industry, where it can be integrated. It is anticipated that using this system in national projects will enhance overall production quality and safety standards. The integration of automation systems into industrial quality control processes is expected to set a new benchmark for ammunition production and quality control, raising awareness in other sectors as well.

1. Introduction

In today's industrial production processes, automation systems operating with high speed and precision are critically important, especially in sectors such as the defense industry. The safety and reliability requirements of defense industry products like ammunition cases are of great significance, as even the smallest defects can lead to serious consequences, endanger user safety, and result in ammunition waste. Therefore, every ammunition case must be flawless and comply with specific standards. NATO has established a series of standards under the name STANAG (Standardization Agreements) to ensure the functionality and compliance of ammunition [1]. These standards include strict rules to ensure quality and safety throughout the process from production to the final use of ammunition cases. NATO standards maintain a common level of quality among member countries and guarantee the reliability and consistent performance of ammunition. These defects are examined under two main categories: visual and dimensional.

Dimensional defects refer to deviations in the geometric measurements of the case and are detected using precision measuring instruments. These defects include critical measurements such as the diameter, length, mouth crimp, and other important dimensions of the ammunition case. Requirements regarding dimensional defects are clearly defined in ammunition standards such as STANAG 4823 [2] and STANAG 2310 [3]. These standards specify the casing tolerances for each type of ammunition and ensure the geometric accuracy of the casing.

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As an example, the geometric dimensions and tolerances of the 5.56x45mm NATO ammunition as determined by NATO standards are presented in the figure below.

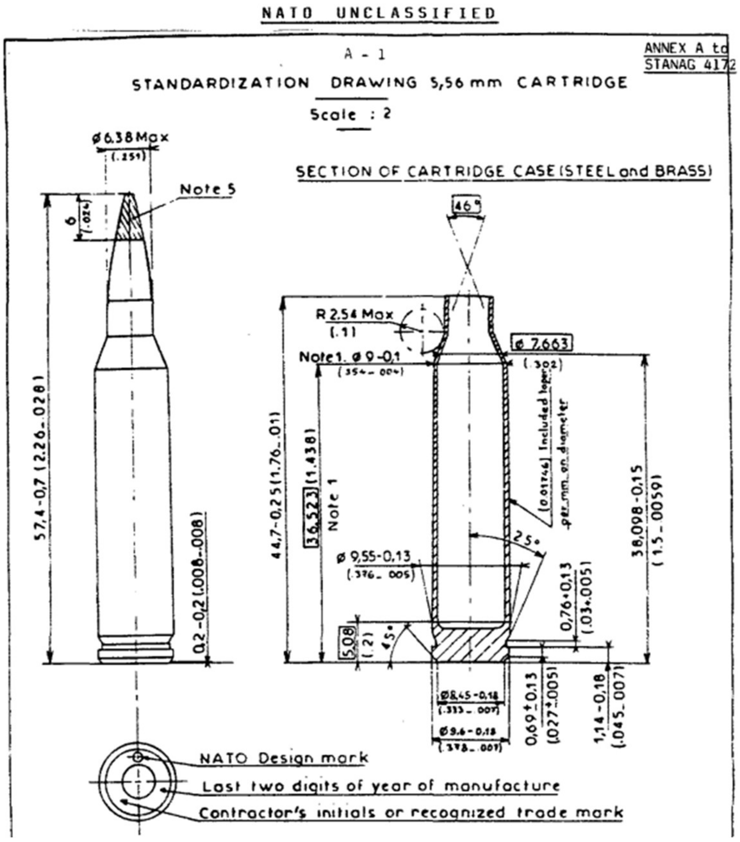

Figure 1. 5.56x51mm NATO ammunition dimensions and tolerances [4]

Visual defects refer to flaws visible on the surface of ammunition cases, either with the naked eye or through more detailed examination using camera images. Common defects such as rust, discoloration, scratches, dents, and deformations are categorized under this group. To classify and inspect these types of flaws, NATO has established detailed standards under AEP-97 [5], ensuring a consistent quality level across member countries. Compliance with these standards requires that ammunition cases not only meet specified dimensional tolerances but also adhere to the defined visual quality criteria. The conditions considered as defects according to NATO standards are summarized in the table presented in the following figure.

ANNEX 6-C

VISUAL STANDARDS OF PRODUCTION DEFECTS

No.#	APPLICABLE CARTRIDGE	4.6mm	5.7mm	5.56mm	7.62mm	9mm	12.7mm
	CASE						
4.	Round Head	X	X	X	X	X[1]	X
5.	Dent (Case)	X	X	X	X	X	X
6.	Split Case	X	X	X	X	X	X
6A.	Incipient Split (Steel Cases)						X
7.	Perforated Case	X	X	X	X		X
8.	Draw Scratch	X	X	X	X	X	X
9.	Scratch (Case)	X	X		X		X
10.	Beveled Underside of Head	X	X	X	X	X	X
11.	Case Mouth not Crimped in Cannelure			X	X	X[2]	X
12.	Scaly Metal (Case)	X	X	X	X	X	X
13.	No Chamfer on Head (Rim)	X	X	X	X	X[3]	X
14.	Fold	X	X		X		X
15.	Wrinkle	X	X		X		X
16.	Buckle	X	X		X		X
17.	Bulge	X	X		X		X
18.	Illegible or Missing Head Stamp (Not Illustrated)	X	X		X		X
19.	Defective Head	X	X		X		X
20.	Defective Mouth	X	X		X		X
21.	No Visible Evidence of Mouth Anneal			X	X		X
21A.	Defective Protective Finish (Steel Cases)				X		X

Figure 2 – Product defects according to NATO visual standards [5]

The product defects listed in the table are evaluated by referencing the visuals provided by NATO for the specified calibers. In the production of ammunition cases, it is essential to ensure strict compliance with established international standards and to guarantee reliable performance during firing and storage under all environmental conditions. In this context, a detailed examination and evaluation of critical parameters such as dimensional tolerances, material properties, and production quality of each ammunition case are required.

Traditionally, quality control of ammunition cases is performed through visual inspection methods based on human observation. In this process, it is necessary to thoroughly inspect parameters such as dimensional tolerances, material properties, and production quality to ensure that each case meets international standards and operates reliably under various environmental conditions. In most countries, quality control processes on ammunition production lines heavily rely on human observation; this slows down processing speeds, limits defect detection capabilities, and increases costs. Human-dependent quality control methods can yield inconsistent results due to factors like fatigue and loss of focus, thereby risking the reliability of ammunition in the defense and security sectors. Precise measurements required by production standards, such as dimensional and geometric tolerances, are not suitable for defect detection by the naked eye.

1.1. Literature review

In the literature, studies focusing on the quality control of ammunition cases and automation systems are quite limited. However, a notable example is the study conducted by Anugool Thamna and his team, titled "Real-Time Visual Inspection and Rejection Machine for Bullet Production" [6]. In this study, a system was developed to automate the quality control of M193 ammunition cases during production. Using high-resolution cameras and digital image processing software, the system detects defects such as dark spots, cracks, deformations, color inconsistencies, and dimensional errors on ammunition cases. The LabVIEW-based image analysis software inspects two ammunitions per second and rejects defective ones through a PLC controller. The results demonstrated that the system could detect defective ammunitions with an accuracy rate of 86.7%. However, the study had some shortcomings. For example, inspecting only two ammunitions per second is significantly below the targeted speed. Moreover, no detailed research was conducted on analyzing and improving the root causes of detected defects. Additionally, the system's flexibility and adaptability to different calibers were not adequately addressed.

Similarly, in another study focusing on percussion caps, an important component in ammunition production, an advanced quality control approach using three-dimensional machine vision systems was introduced. The study by Tellaeche and Arana highlights a 3D machine vision system developed for quality control in the high-volume production of percussion caps for shotguns [7]. The study emphasized that conventional image processing methods were insufficient against production-specific challenges such as reflections, fast movement, and mechanical irregularities. Thus, various machine learning algorithms were employed to classify types of defects. The system, capable of inspecting approximately 216,000 units per hour in real time, demonstrates the effectiveness of machine vision technologies in the automatic quality control of ammunition components.

Studies on surface defect detection using image processing technologies are quite common. Thanks to high-resolution cameras and advanced algorithms, even microscopic defects on metal surfaces can be detected with high accuracy. Modern quality control systems, leveraging these technologies, perform tests and measurements faster and more reliably, thereby enhancing production efficiency.

For instance, in the study by Moru and Borro on gear production, the Vision2D system was developed, integrating cameras, sensors, and robotic control to inspect gears with high precision [8]. After calibration, the system achieved an error margin of only 0.06 pixels, showcasing the contribution of machine vision technologies to industrial accuracy and efficiency.

Similarly, the study by Huang and Ma examined the use of machine vision technologies to detect defects on the mouth, base, and wall regions of empty bottles [9]. In their work, a unique method called Circular Region Projection Histogram (CRPH) was developed for fast production lines; this method aligned images and compared them against references to detect surface defects with high accuracy. This system significantly improved the speed and efficiency of quality control in bottle inspection processes.

Furthermore, the study by Wu, Qin, and Wang highlighted the advancement of these technologies through a UAV-based visual inspection method developed for detecting defects on railway surfaces [10]. The study applied Local Weber-like Contrast (LWLC) for image enhancement and Gray Stretch Maximum Entropy (GSME) for defect segmentation. Together, these methods successfully detected surface defects even under varying lighting conditions, demonstrating the effectiveness of UAV-based systems in quality control.

In the work by Tomohira Tabata and colleagues, surface defects on rotating cylindrical objects were successfully detected at a frame rate of 1,000 frames per second using high-speed cameras [11]. Specialized software was used to eliminate image distortions and lighting issues, achieving high speed and accuracy in quality control processes.

All these examples clearly illustrate how image processing technologies have transformed quality control processes across various industries. In the design of such complex systems that incorporate advanced technologies like image processing, the "Systematic Design Methodology" developed by Gerhard Pahl and Wolfgang Beitz [12] emerges as a crucial tool. Numerous successful machine designs developed based on systematic design principles can be found in the literature. However, although many studies have applied systematic design methodology in the general field of machine design, there are no open-source studies specifically focusing on machine designs for the ammunition sector. Below, several machine design studies developed in accordance with systematic design principles are presented as examples.

In the olive harvesting machine design developed by Börklü and Top [13], the systematic design approach of Pahl and Beitz was followed to propose a conceptual machine solution according to producer requirements. Similarly, in the study by Biçer and colleagues, a new shopping cart was conceptually designed using systematic design steps to address ergonomic and usability issues of existing models [14].

In another study conducted by Kerket and Azlan [15], a vertical conveyor system was designed to improve manual handling methods in the rubber industry. The design process was carried out based on the Pahl and Beitz methodology, providing a detailed engineering solution according to technical requirements.

In the study by Rosa and Rodiawan [16], a pepper peeling machine was developed within the framework of systematic design principles, offering a mechanical solution to replace manual peeling while ensuring low energy consumption and high efficiency.

1.2 Proposed quality control system and its contributions

Unlike previous examples, the system developed in this study integrates both systematic design methodology and advanced image processing technologies, thereby maximizing both design efficiency and defect detection accuracy in the quality control process. The developed system not only offers a machine design but also addresses the specific quality control requirements of the ammunition sector, combining high precision, speed, and full automation in a single solution.

The system is designed to be integrated into the production line and is capable of inspecting up to 320 ammunition cases per minute. It is equipped with high-resolution cameras, specialized lighting elements, and advanced image processing algorithms. Through a continuous feeding mechanical structure, the system ensures that ammunition cases move at high speed and in an orderly manner without compromising their physical and structural integrity.

Beyond defect detection, the system records the types and recurrence rates of defects, enabling root cause analysis. This approach allows not only the removal of defective products but also the early detection of structural problems that may arise during the production process, thereby improving overall production efficiency. Unlike many conventional systems, this analytical capability transforms quality control from a final inspection step into a proactive tool for continuous process improvement.

The domestically developed system stands as one of the first of its scale in Turkey and outperforms existing international counterparts in terms of both speed and flexibility. Its ability to adapt to different ammunition calibers (7.62 mm, 5.56 mm, 9 mm) and its integrated defect analysis capability bring not only quality control but also continuous improvement and flexible production potential to manufacturing processes. In conclusion, this system presents an innovative solution aimed at significantly enhancing quality, productivity, and competitiveness standards, particularly in sectors like defense, where high precision and reliability are essential.

2. Design Methodology

The design process of this machine, intended to automate the quality control of ammunition cases with high speed and accuracy in a modular system, can be considered a complex engineering problem. To simplify and optimize the solution process, the "Systematic Design Methodology" developed by Gerhard Pahl and Wolfgang Beitz for product design was employed [12].

Systematic design is a widely recognized methodology in engineering disciplines, enabling the management of complex design problems by dividing them into manageable sections. Conducting the conceptual design as the first phase of the design process significantly facilitated and streamlined the project. Conceptual design establishes the overall framework and roadmap of the project, laying a foundation for the subsequent stages of the design. In the development of a complex machine like the ammunition case quality control system, this early phase allowed for identifying the optimal solution among design alternatives and enabled the early detection of potential risks and the avoidance of foreseeable costs.

Within the framework of this comprehensive methodology, a requirements list was prepared as the initial phase of the project. This list forms the foundation of the systematic approach, providing the essential information and guidance needed for the subsequent stages of the design process.

2.1. Requirement List

The requirements list (design specification) [17], prepared for the ammunition case quality control machine is presented in Table 1. This list summarizes the key features and requirements that must be considered during the design of the machine. It covers critical factors such as the machine's ability to process ammunition cases of different calibers and specifications with high accuracy and speed, ease of use, and maintenance requirements. Additionally, the ergonomic design and operational efficiency of the machine were also taken into account. The needs identified at this stage form the foundation of the conceptual design process and can be flexibly adapted in the later stages of the design. The features listed in the specification include not only mandatory requirements but also desirable features that can be achieved within technological and economic constraints.

Table 1. Requirements list

NO	Required Features / Needs
	Functional Requirements:
1	The machine must be able to inspect at least 320 ammunition cases per minute.
2	It must be capable of processing ammunition cases with various calibers and specifications.
3	It must be able to detect defective cases and categorize them appropriately.
	Performance and Reliability:
4	The machine must operate with high reliability and minimal maintenance during continuous operations.
5	The system must detect defects with an accuracy rate above 99%.
	Automation and Software Features:
6	The machine must perform automatic quality control using advanced image processing technologies.
7	The software must classify defects and identify elements causing production errors.
	Ergonomics and User Interface:
8	(A) The machine must be designed to provide easy and safe operation for operators.
9	The interface must be user-friendly and easy to understand.
	Safety and Environmental Standards:
10	The machine must be manufactured and quality-controlled in accordance with national and international safety standards (e.g., MIL-STD and EN ISO).
11	(A) It must be energy-efficient to minimize environmental impact during operation.
	Interface Requirements:
12	The machine must have mechanical and electrical interfaces compatible with existing production lines.
13	(A) The system should have the capacity to integrate with production management systems (ERP/MRP).
	Testing and Validation Criteria:
14	The machine's performance must be validated through tests simulating real production conditions.
15	Functional tests must be designed to cover all ammunition calibers and types.
	Documentation and User Training:
16	(A) Detailed user manuals and maintenance instructions must be provided with the machine.

2.2. Function Diagram

The functional structure of the ammunition case quality control system is based on the use of energy (mechanical and electrical), material (ammunition cases), and signals (control and image processing commands) as system inputs. These resources enable the high-speed and accurate inspection of ammunition cases with varying calibers and specifications. Basic functions such as retrieving cases from the feeder, positioning, defect separation, and transferring through the inspection station are carried out sequentially. Figure 3 illustrates the cooperation of the system, showing the flows of energy, material, and signals between the functional blocks.

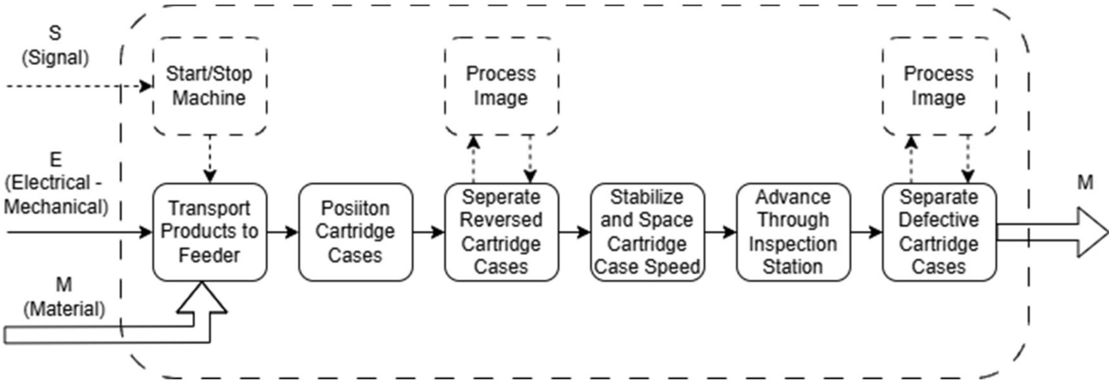

Figure 3. Function diagram of the ammunition case quality control system

These system functions are systematically analyzed and divided into main and auxiliary functional blocks, including collection, positioning, acceleration, and separation. Each functional block has been optimized to ensure smooth transitions, consistent operation, and overall system efficiency. The organized structure enhances the reliability and repeatability of the inspection process, contributing to both operational stability and high performance under continuous production conditions.

2.3. Subsystems and overall design

After defining the functions identified in the function diagram as presented in the table, possible solutions were developed to fulfill these functions and optimize the overall system performance. These solutions are listed in the morphological matrix shown in Figure 4. Each main function, along with its possible sub-solutions, is included in this matrix.

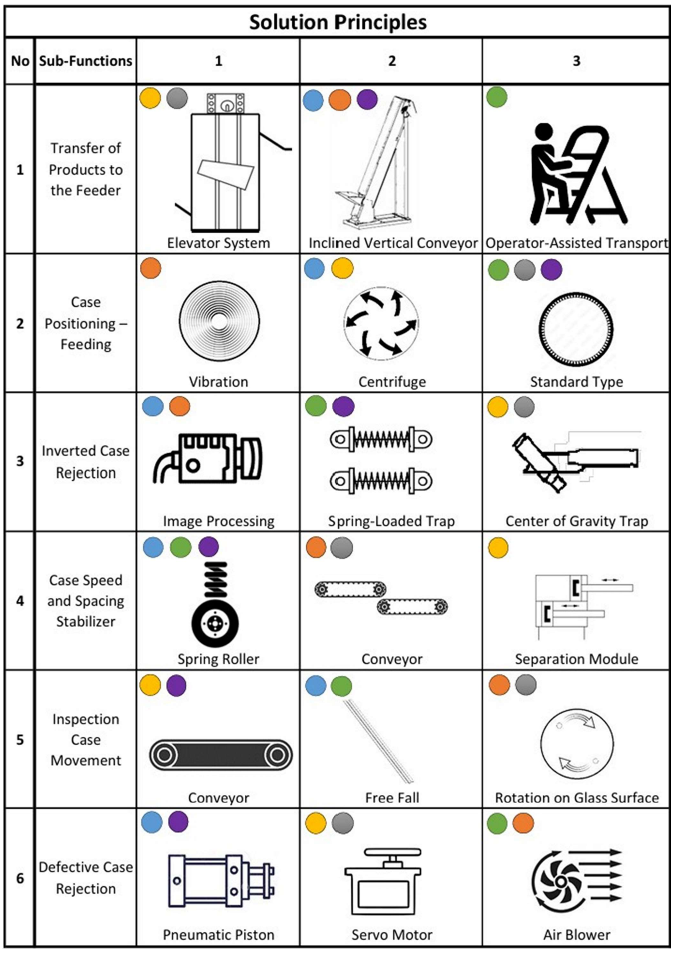

Figure 4. Morphological chart

In this process, various design variants were developed for each sub-function, and optimal solution combinations for the system were created as shown in Table 2. These sub-designs are detailed to meet technical and practical requirements in order to ensure more efficient, faster, and error-free operation of the system. Critical processes such as feeding the ammunition cases, positioning them, adjusting their speeds, and separating defective products directly affect the overall system efficiency. In the next step, alternative solutions for each main function were explored to identify the most efficient and practical options.

Table 2. Design options

Option 1		*1.3 – 2.3 – 3.2 – 4.1 – 5.2 – 6.3*
Option 2		*1.2 – 2.2 – 3.1 – 4.1 – 5.2 – 6.1*
Option 3		*1.2 – 2.1 – 3.1 – 4.2 – 5.3 – 6.3*
Option 4		*1.2 – 2.3 – 3.2 – 4.1 – 5.1 – 6.1*
Option 5		*1.1 – 2.2 – 3.3 – 4.3 – 5.1 – 6.2*
Option 6		*1.1 – 2.3 – 3.3 – 4.2 – 5.3 – 6.2*

2.4. Preliminary evaluation

The requirements list, function diagram, and morphological matrix prepared for the ammunition case quality control machine detail each part of the design and present possible sub-functional components and solution alternatives within the system. Thanks to the diversity of sub-designs, six different alternative design solutions for the system have been proposed. To select the most suitable alternatives, an evaluation must be carried out based on defined criteria. This evaluation involves a preliminary screening process considering all specified measures. The selection card or preliminary design evaluation table (Figure 5) allows for a systematic review of how each design alternative performs against these criteria.

SELECTION CARD

Solution Options (SO)

SOLUTION OPTION
(+) Yes
(-) No
(?) Insufficient Information
(!) Check the Requirements List

DECISION
Mark the solution options
(+) Continue with the solution
(-) Eliminate the solution
(?) Gather information, re-evaluate the solution

A: Meeting Specification Requirements
B: Compliance with all functions
C: Performans ve doğruluk
D: System reliability
E: Design optimization
F: Cost-effectiveness
G: Modular and flexible design
H: Sufficient information

SO		A	B	C	D	E	F	G	H	Notlar (işaretler, nedenleri)	DECISION
S1	1	-	-	-	+	-	+	-	+	Low cost but dependency on operator	-
S2	2	+	+	+	+	+	-	+	-	Additional camera and processor cost	+
S3	3	-	-	?	?	+	+	-	-	Reliability and information deficiency in rotation module	-
S4	4	+	+	?	-	+	+	-	+	Difficult to adapt to different calibers	+
S5	5	+	+	-	-	+	-	+	+	Need for bunker, reliability deficiency	+
S6	6	+	+	-	-	-	-	+	-	Risk of jamming in trap and potential for performance decrease	-

Figure 5. Design preliminary evaluation table

First, the criterion "Compliance with Specification Requirements" evaluates whether the machine design meets the defined technical specifications and user needs. The "Compatibility with All Functions" criterion measures how well the machine ensures integration and coordination between different functions and operations. "Performance and Accuracy" assesses the machine's ability to provide quick and reliable results with a high defect detection accuracy, while "System Reliability" examines the machine's long-term operational durability and its capacity to minimize failure rates. "Design Optimization" investigates whether the design achieves an ideal balance between simplicity, functionality, and manufacturing processes. This criterion also indicates how effective the machine is regarding material usage and energy efficiency. "Cost Effectiveness" highlights the economic value of the machine based on the total cost of ownership, including investment return time, operating, and maintenance costs. The "Modular and Flexible Design" criterion determines how quickly and effectively the machine can adapt to different ammunition calibers and changing operational requirements, providing flexibility for future expansions or reconfigurations. "Sufficient Information" evaluates the adequacy and accessibility of technical knowledge used during the design and development stages, ensuring the continuity and accuracy of information flow throughout the design process.

In the selection card presented in Figure 5, each solution alternative is evaluated according to the established criteria using the indications "(+) Yes", "(-) No", "(?) Insufficient Information", or "(!) Check Requirements List". This evaluation determined whether each design should be continued, eliminated, or required additional information. These criteria systematically reveal the compliance levels of the design alternatives and form the basis of the preliminary screening process. As a result of this preliminary evaluation, the most suitable design alternatives were selected, and the project advanced to the next stages. Thus, the goal was to ensure that the machine would operate with maximum efficiency and effectiveness from both technical and operational perspectives.

2.5. Design solutions

Following the general evaluation conducted based on the selection card presented in Figure 5, a detailed analysis of each solution alternative against the defined criteria is presented below.

Solution 1 stands out as an economical and feasible option due to its low cost and simple structure. Systems such as manual product handling by the operator, a standard-type feeder, a spring-loaded mechanical trap, and a blower offer advantages such as ease of maintenance, low risk of failure, and high accessibility to technical information. Thus, Solution 1 is positively evaluated in terms of system reliability, cost-effectiveness, and information-based feasibility. However, the manual handling of products significantly limits the system's level of automation, weakening both the compliance with technical specifications and the functional integrity of the design. Additionally, simple components like the standard feeder and spring trap offer limited performance in operations requiring high precision, falling short in performance and accuracy. The reliance on manual operation and the lack of structural flexibility are also considered inadequate regarding design optimization and modularity. Overall, although Solution 1 offers certain advantages, it remains limited in meeting technical and functional expectations.

Solution 2 is evaluated as a functionally strong alternative due to its high level of automation and broad compliance with technical specifications. Components such as vertical conveyor product transfer, a centrifugal-type feeder, and a reverse ammunition separation system based on image processing technologies enable the system to deliver high accuracy and processing performance. It is known that centrifugal-type feeders offer higher feeding speeds compared to other types, which further supports the system's efficiency [18]. The use of flow stabilization via spring rollers and defective case separation via pneumatic pistons supports the system's operational reliability. As a result, Solution 2 presents a positive profile regarding technical competence, functional integrity, reliability, design balance, and system modularity. On the other hand, the inclusion of additional hardware such as cameras and processors increases the overall cost, and the centrifugal feeder's lack of field testing, along with insufficient documentation for system components, points to some weaknesses in information reliability. In general, Solution 2 offers high technical performance but requires further technical clarification and cost balancing.

Solution 3, despite offering some structural advantages, is considered an alternative with serious technical uncertainties and deficiencies. The inspection method based on rotating on a glass surface provides a simple structural solution, but its lack of practical testing raises significant doubts about performance and system reliability. Insufficient fulfillment of essential functions like product transfer and feeding weakens its compliance with technical specifications and functional integrity. Furthermore, the lack of detailed technical information about the system components and the absence of foresight regarding potential operational problems negatively affect its information reliability. Although the simplicity of the structure and the limited number of components provide advantages in design optimization and cost-effectiveness, the overall technical inconsistencies and lack of information suggest that Solution 3 offers limited feasibility.

Solution 4 is evaluated as a balanced alternative in terms of functionality and structural simplicity. The use of well-known systems like a vertical conveyor for product transfer and a standard feeder supports compliance with technical specifications, capacity to fulfill all functions, design simplicity, cost advantage, and accessibility to technical information. However, the use of simple systems like a spring-loaded mechanical trap for reversed case separation could limit performance and accuracy, particularly in precision-required operations. Additionally, limited compatibility with different ammunition calibers is considered a shortcoming in terms of modularity and flexibility. Overall, despite strong technical attributes, certain operational limitations are noted.

Solution 5 is evaluated as a hybrid structure containing innovative technical components but also bearing some weaknesses in cost and reliability. The elevator system used for product transfer and the center-of-gravity-based trap mechanism for reversed case separation introduce space requirements and limit long-term operational reliability. Nevertheless, the use of advanced components like a centrifugal feeder, separation module, and servo motors supports modularity, functional simplicity, and accessibility to technical information. Especially the servo motor-driven separation mechanism ensures high precision, and the separation module offers flexibility to work with different calibers. However, the complexity and increased cost resulting from these technologies present disadvantages in terms of performance, reliability, and economic feasibility. Therefore, while Solution 5 offers strong technical components, careful optimization is necessary.

Solution 6, despite incorporating some innovative components, falls short in meeting general system performance and technical requirements. The elevator system used for product transfer creates additional space requirements, and the standard-type feeder, although a low-cost option, offers limited efficiency due to the risk of ammunition jamming. The center-of-gravity-based trap used for reversed case separation does not meet performance and accuracy expectations. The selection of untested components such as the glass surface rotation inspection method and the center-of-gravity trap also leads to deficiencies in information adequacy. Moreover, despite its complex structure, this solution fails to deliver the expected technical advantages and exhibits weaknesses in design optimization, cost-effectiveness, and compliance with technical specifications. Although partial modularity is achieved through the use of servo motors and replaceable components, Solution 6 overall presents limited technical and operational success.

After a detailed examination and evaluation of all solution alternatives based on the defined criteria, three design options with prominent shortcomings were eliminated during the preliminary screening process. The remaining three design alternatives (Option 2, Option 4, and Option 5) were found suitable in terms of technical competence and functional integrity and will be subjected to further selection stages. At this stage, the final choice among the evaluated options will be made based on each design's functional advantages and the prioritized criteria. Although all three alternatives offer effective solutions for ammunition case quality control, a more detailed analysis is required to select the most suitable one. In this context, the "goals tree" method will be used to conduct the selection process in a more systematic and objective manner.

2.6. Additional selection procedures

At this stage, a "goals tree", shown in Figure 6, was created as an effective tool to evaluate how well each design alternative meets the overall objectives by defining the priorities and importance levels of each function and feature of the design. Through this method, design criteria and sub-criteria were identified, weighted values were assigned to each, and the three design alternatives were analyzed and compared in detail according to these values.

The goals tree presented in Figure 6 include three main criteria groups: Technical Characteristics, Flexibility, and Cost.

Under each main criterion, sub-criteria are defined, and weights are assigned to indicate their relative importance. The symbol W represents the relative weight of a criterion within its own group, while "Wt" indicates its weight within the overall system. For example, for the "Speed and Efficiency" criterion, W = 0.4 denotes its importance within the "Technical Characteristics" group, while "Wt" = 0.24 represents its overall impact across the entire system. In this way, the total weight values "Wt" affecting the overall system were calculated and normalized to sum to 1. This structure enables the contribution of each criterion to the system's performance to be quantitatively assessed, allowing for a comparative analysis of the design alternatives based on these measures.

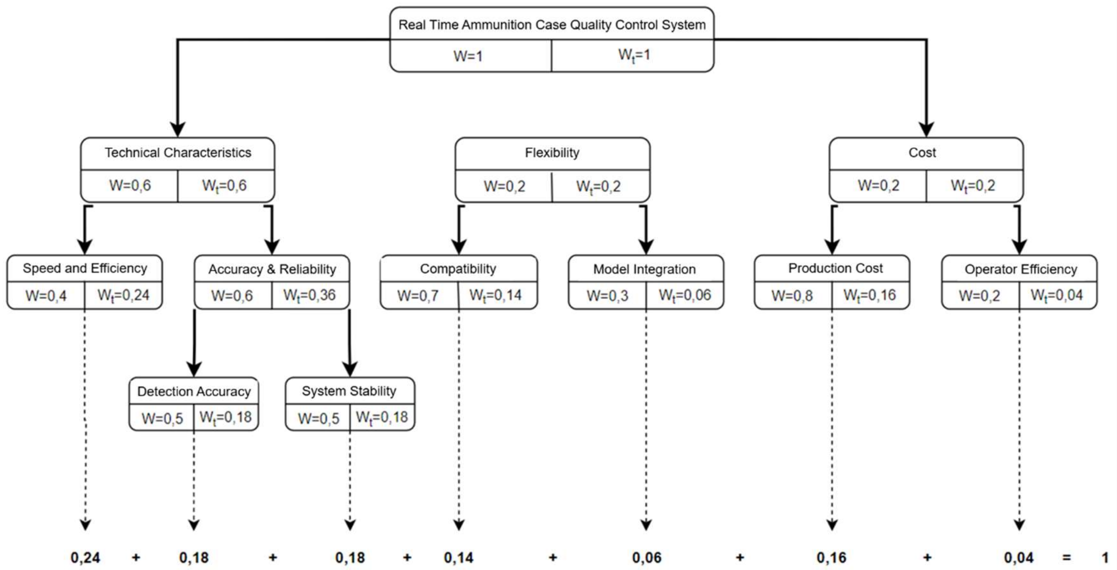

Figure 6. Goals tree (criteria value diagram)

In line with the criteria structure defined by the goals tree, the impact of each sub-criterion on the system was individually considered, and the extent to which each design alternative met these criteria was evaluated from a technical perspective. Below, these evaluations are presented under each criterion heading along with their justifications.

In terms of "Speed and Efficiency", Option 5 demonstrates an advantageous structure thanks to stable transportation provided by the elevator system and the precise and controlled operation offered by the servo motor-based separation system. This solution has the potential to enhance production flow regularity and efficiency, particularly in terms of speed. Option 2, on the other hand, achieves fast mechanical flow through the use of a vertical conveyor system and free-fall method, which can help shorten production time. In Option 4, the conveyor systems and spring-loaded mechanical trap used offer a more controlled but relatively slower process, which may result in limited performance in terms of speed and efficiency compared to the other alternatives.

Regarding "Detection Accuracy", Option 2, equipped with image processing technology, has a high potential for achieving high defect detection accuracy. This technology enhances the system's accuracy level by identifying surface defects without requiring human intervention. The center-of-gravity-based trap and servo motor-driven separation systems used in Option 5 offer improved mechanical precision but do not provide as advanced an analysis capability as image processing. Option 4, which uses a spring-loaded mechanical trap, stands out for its structural simplicity but offers limited precision and a relatively higher error tolerance.

In terms of "System Stability", Option 2, with components such as spring rollers and pneumatic pistons that are widely used and have long operational histories, presents a stable and reliable working structure. The use of proven components contributes to the system's overall operational stability. Option 5, while incorporating precision components such as a servo motor, offers higher control but is more dependent on careful maintenance and calibration. Option 4, which relies on manual and spring mechanisms, provides ease of use but, over time, mechanical wear and inconsistencies could lead to reduced stability.

Regarding “Compatibility with Existing Models”, Options 2 and 4 include components that can be easily integrated into existing and standard production systems. Elements such as vertical conveyors, spring traps, and pneumatic pistons are compatible with many current production lines. Option 5, however, includes more specialized components such as a centrifugal-type feeder and a servo motor, which may require additional adaptations during integration, potentially creating challenges for compatibility with existing production lines.
In terms of “Model Integration”, Option 2 has a strong profile due to its compatibility with advanced technologies, and its flexible modular structure supported by image processing and pneumatic systems enables easier integration with new models. Option 5, with its separation module capable of handling different calibers, offers advantages in terms of expandability. In contrast, Option 4, with more mechanical and rigid components, presents a more limited capability for adaptation to model diversity and integration.

Through these technical evaluations conducted for each criterion, a comprehensive analysis of the performance of each design alternative has been completed. Based on these analyses, a comparative evaluation using numerical scoring was carried out, and the results are presented in Figure 7.

Evaluation Table					Option 2			Option 4			Option 6		
	Criterion	W	Parameters	Description	Ratio	Score	Weighted Score	Ratio	Score	Weighted Score	Ratio	Score	Weighted Score
1	Speed and Efficiency	0,24	Speed	Control Speed	High	9	2,16	Medium	6	1,44	High	10	2,4
2	Detection Accuracy	0,18	Success	Defect Detection Success	High	9	1,62	High	8	1,44	High	8	1,44
3	System Stability	0,18	Reliability	Low Fault and Error Tendency	High	9	1,62	Low	4	0,72	Low	4	0,72
4	patibility with Existing Mo	0,14	Flexibility	Capability to Operate with Different Calibers	High	9	1,26	High	9	1,26	High	8	1,12
5	Model Integration	0,06	Modularity	Capability to Integrate New Technologies and Modules	High	8	0,48	Medium	6	0,36	Medium	7	0,42
6	Production Cost	0,16	Cost	Cost Effectiveness	Medium	6	0,96	High	9	1,44	Medium	6	0,96
7	Operator Efficiency	0,04	Cost - Safety	Reduced Labor Cost and Human Factor	Medium	7	0,28	Medium	8	0,32	Medium	9	0,36
$\sum W_t = 1$					$\sum d_2 = 57$			$\sum d_4 = 50$			$\sum d_5 = 52$		
					$\sum A\,d_2 = 8{,}38$			$\sum A\,d_4 = 6{,}98$			$\sum A\,d_5 = 7{,}42$		

Figure 7. Evaluation table

In Figure 7, the previously determined weight values (W) for each criterion were used, and each design alternative was scored between 1 and 10 according to these criteria. Then, these scores were multiplied by the corresponding criterion’s weight to calculate the "Weighted Score." For example, for Option 2 under the Speed and Efficiency criterion, the score is 9, which, when multiplied by the criterion weight of 0.24, results in a weighted score of 2.16. This process was repeated for all criteria, and the total score (∑d) and total weighted score (∑Ad) for each alternative were calculated. For Option 2, the total score was 57 and the total weighted score was 8.38. When compared with the other alternatives, this value indicates that Option 2 has the highest performance.

The advantages offered by Option 2, when considering the initial costs, are balanced by its long-term benefits. Although it involves a higher initial investment, the machine’s increased precision and reduced failure rate are expected to contribute to lower operational costs over time. For these reasons, Option 2 has been evaluated as the most suitable choice for the design of the ammunition case quality control machine.

2.7. Final design and details

As a result of the systematic evaluations and criteria-based analyses conducted in this study, Option 2 was determined to be the most suitable design alternative, and the final design was shaped based on this selection. In the final design, the most appropriate components were chosen for each functional requirement, and an integrated structure was established to optimize the overall system performance.

In the initial stage of the designed system, a high-capacity conveyor belt system was employed for the collection and feeding of ammunition cases. The ammunition cases are gathered in a 40-liter hopper with a capacity of approximately 20,000 cases, providing sufficient stock for continuous and long-term production processes. A mechanism with adjustable transfer speed was developed to ensure the regular transfer of cases from the hopper to the conveyor belt. This mechanism features an adjustable outlet at the hopper exit, regulating the drop of the cases onto the belt, thus optimizing the transfer speed to approximately 300–350 cases per minute. This regular and controlled flow enhances the efficiency of the feeding process and contributes to the orderly advancement of ammunition cases toward the inspection station, thereby maximizing the accuracy and efficiency of the inspection operations. The conveyor used in this stage of the system is shown in Figure 8.

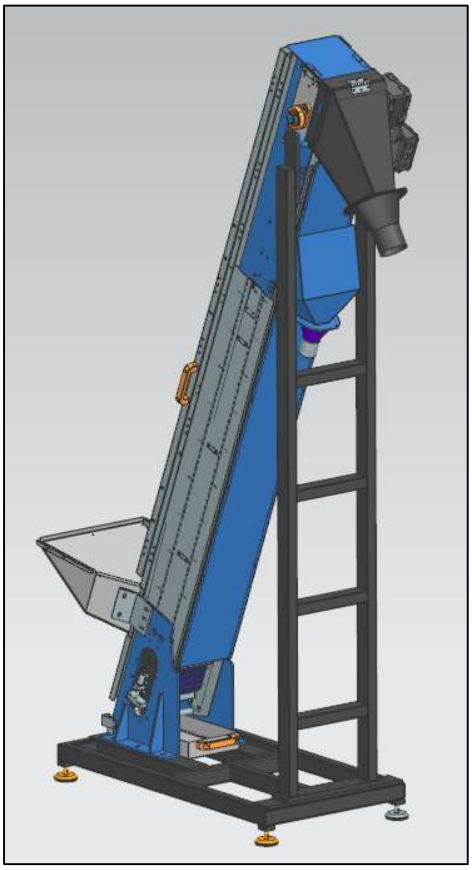

Figure 8. Inclined vertical conveyor

The ammunition cases transferred from the conveyor belt to the centrifugal-type feeder are guided by two main rotating systems. The inner dome disk generates centrifugal force, propelling the cases outward and transferring them to the outer system called the lateral cylinder. The lateral cylinder, assisted by a guiding plate, quickly and regularly directs the cases along its outer surface toward the feeder's exit. At this stage, a camera-based image processing system positioned at the exit checks whether the ammunition cases are in the correct orientation. Cases detected in an inverted position are redirected back into the system using an integrated air-blowing mechanism to re-enter the cycle. The inner and outer rotating systems are independently driven by motors and gear-chain mechanisms, and torque limiters are installed on the motor output shafts to ensure system safety.

The general structure and working principle of the centrifugal feeder, along with the reverse ammunition case separation mechanism using image processing, are shown in Figure 9.

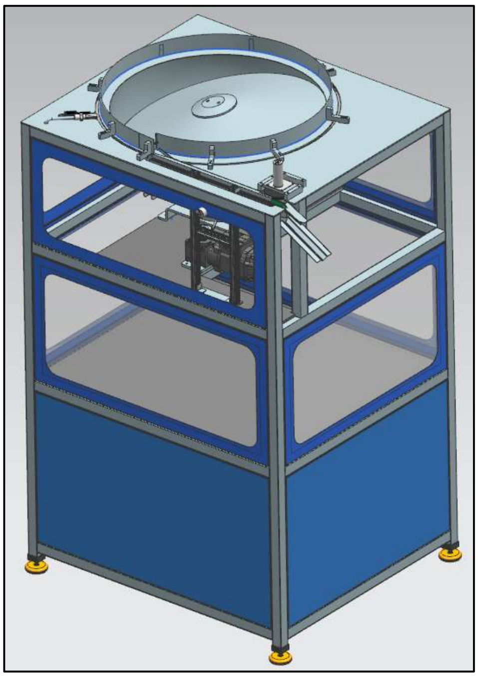

Figure 9. Centrifugal feeder and image-based reverse ammunition case separation

The ammunition cases, properly aligned as they exit the feeder, move along a short conveyor belt located on the same unit and reach the spring roller system. In this system, a spring-loaded roller rotating at a constant speed forces the cases to match its speed, thereby stabilizing the product flow and regulating the spacing between consecutive cases. Thanks to this regular spacing, the cases arrive at the inspection station at a constant speed and with consistent intervals, enabling a more efficient inspection process. A model of the spring roller system is presented in Figure 10.

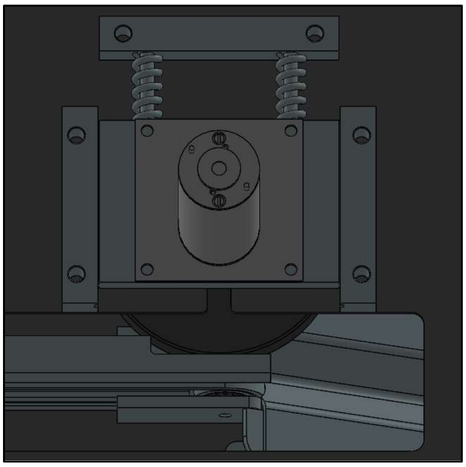

Figure 10. Spring roller system for stabilizing ammunition case flow

After exiting the roller mechanism, the ammunition cases enter a glass tube located in the inspection station, shown in Figure 11 and continue to move along a fixed line at a constant speed. The use of a glass tube ensures the preservation of the cases' position and provides stable imaging through homogeneous light distribution. This structure eliminates the reflection and shadow problems previously caused by metal surfaces, thereby improving the accuracy of the inspection process.

Figure 11. Inspection station and free-fall movement of ammunition cases inside the glass tube

At the inspection station, the cases undergo a three-stage quality control process. In the first stage, the mouth and primer areas of the cases are inspected. A total of two high-resolution cameras are used for this task. The first camera is placed at a slight angle between the glass tube and the case axis to directly capture the mouth area of the case, allowing for a clear frontal view. The second camera is similarly positioned to focus on the primer end of the case. Both cameras are supported by circular light sources to ensure homogeneous illumination, enabling accurate detection of surface defects such as cracks, deformations, or missing areas in the mouth and primer regions.

In the second stage, the diameter and length measurements of the cases are performed. These measurements are conducted using a profile measurement device (laser sensor or optical scanner), and the measurements taken from the side surfaces of the cases are compared against predefined dimensional tolerance ranges.

In the final stage, a full surface scan of the cases is performed. During this process, the cases are rotated 360 degrees around a fixed axis and observed from different angles by eight high-resolution cameras positioned at equal intervals around the case. The cameras are arranged circularly at 45° angles, comprehensively scanning areas such as the side surface, edge transitions, and the primer circumference of the cases. As a result, surface defects such as scratches, holes, dents, or discolorations are detected with high precision.

All images obtained from these stages are collected via the camera and sensor systems and transmitted to the processor. The processor analyzes the images from the mouth, primer, dimensional, and surface areas of the cases using predefined image processing algorithms. During this analysis, the cases are evaluated according to the limits defined by NATO standards to determine whether any defects or non-conformities exist. The system automatically inspects each case based on the relevant control regions and identifies any conditions that fall outside the standards. This process is conducted entirely automatically, determining the conformity status of each product without human intervention. Information regarding defective cases is transmitted to the processor and recorded in the system for use in the subsequent separation stage. Thus, the quality control process is carried out quickly, reliably, and in full compliance with the standards.

At the end of the inspection process, approved products continue along the production line, while defective products are separated according to their defect types. The separation process is carried out using pneumatic pistons and sensor systems positioned at the exit of the inspection station. Ammunition cases identified as belonging to a specific defect class are detected by the relevant sensors and physically pushed into appropriate output bins by pneumatic pistons. In this way, cases with repairable defects are directed to special compartments, while only severely damaged products are sent to the recycling line. This system not only separates defective products but also significantly contributes to root cause analysis of production defects, quality improvements, and the enhancement of production efficiency. The general layout of the machine and the separation unit is schematically shown in Figure 12.

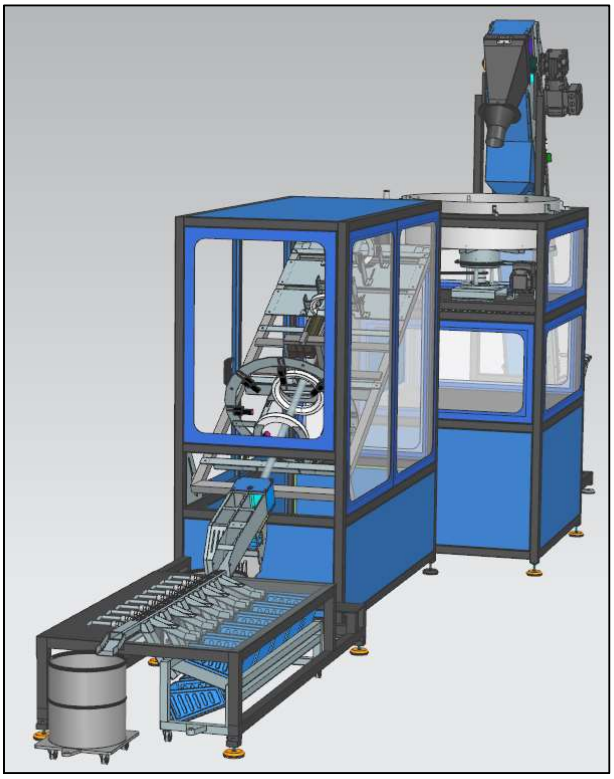

Figure 12. Defect separation unit and machine layout

All mechanical components, optical systems, and advanced image processing algorithms included in the design have been configured to operate in an integrated manner. The developed software analyzes the images captured by the cameras, detects potential defects on the ammunition cases, and classifies these defects according to NATO standards. The mechanical conveying systems, optical scanning assemblies, and software infrastructure work together to deliver a high-precision, fast, and reliable quality control process. The overall structure of the designed system and the layout of all functional units are shown in Figure 13.

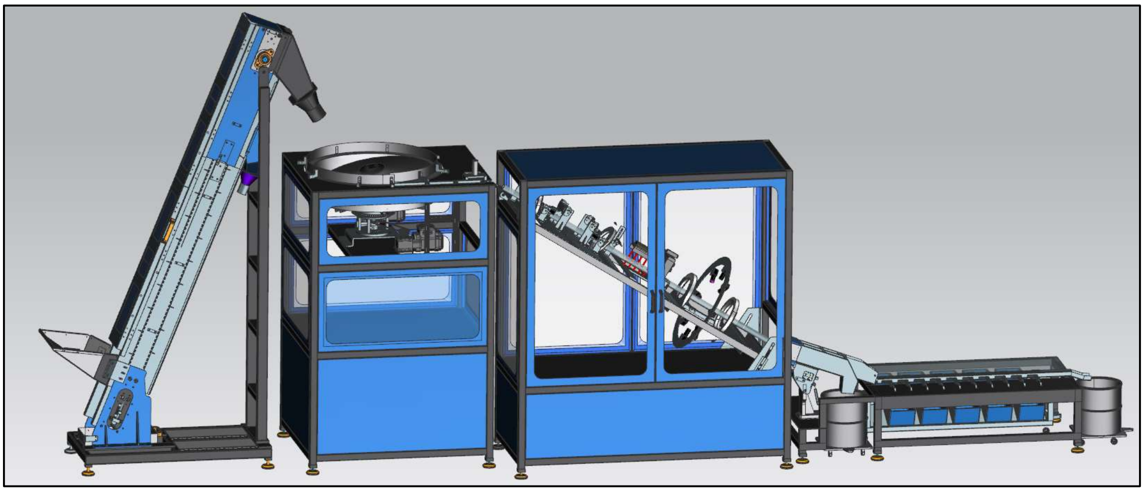

Figure 13. Overall structure and functional unit layout of the designed ammunition case quality

3. Conclusions

This study presents a critical advancement in the efforts to automate and improve quality control mechanisms in the production processes of ammunition cases. The developed system is designed to enable the continuous production of ammunition cases in compliance with NATO standards, ensuring high speed and accuracy. Unlike traditional quality control methods based on human intervention, this automated system accelerates production processes, minimizes error rates, and significantly reduces costs. Additionally, the machine enables more effective identification of the root causes of production defects through defect analysis, allowing the obtained information to be shared across other phases of the production process to support continuous improvements.

Moreover, the system has been developed using a modular structure, incorporating replaceable parts and adjustable mechanisms specifically designed to quickly and efficiently adapt to various ammunition case calibers such as 7.62 mm, 5.56 mm, and 9 mm. This modular approach enhances the production line's speed and efficiency while providing the ability to swiftly respond to different product demands. The practical modifications integrated into the machine allow easy reconfiguration for various product types, enabling manufacturers to respond more flexibly to changing market demands.

In the literature, studies focusing on the automated quality control of ammunition cases are quite limited. One of the few examples is the study conducted by Thamna (2018), where a system was developed for the visual inspection of M193-type ammunition cases. This system was configured to detect only four types of defects (cracks, tears, wrinkles, and dimensional deviations) and was evaluated solely based on a single case type. The study primarily focused on identifying basic surface defects through camera imaging; dimensional measurements and comprehensive surface analyses were not incorporated into the system design. Furthermore, this study did not focus on direct machine design but rather developed a quality control setup tested at the prototype level in a laboratory environment. The system's performance under industrial conditions or for defense industry applications was not assessed.

In contrast, the system developed in this study features multi-stage quality control processes targeting different regions of the ammunition case (mouth, primer, and lateral surface), offering a comprehensive defect detection mechanism including dimensional measurements (diameter, length) and full 360° surface scanning. Not only surface defects but also dimensional deviations and other microscopic errors resulting from the production process are detected with high precision. The developed system is adaptable to different types of ammunition cases, and each product is evaluated according to NATO quality standards. Moreover, the system is fully designed for industrial use and configured to operate reliably under field conditions for extended periods.

From this perspective, the current study goes beyond the limited examples in the literature, offering a more comprehensive, precise, and durable quality control solution for sectors requiring high reliability, such as the defense industry.

Additionally, the system contributes significantly to occupational safety and employee ergonomics by helping to prevent workplace accidents and occupational diseases. Studies examining Occupational Health and Safety (OHS) risks in ammunition production have shown that exposure to chemical substances and high noise levels can cause serious health problems, such as hearing loss and respiratory system disorders [19]. Such health risks directly threaten workers' health and safety while also negatively impacting productivity. On the other hand, manufacturing lines integrated with automated systems reduce employees' exposure to repetitive and physically demanding tasks, allowing them to focus on more strategic and value-creating activities. This not only creates a healthier and more productive working environment for both employers and employees but also supports improvements in overall productivity and efforts to protect workers' health.

Given that no other machine with similar features has yet been produced domestically, this automation system has significant potential to increase local production capacity and reduce dependence on foreign technologies in the defense industry. The developed machine can efficiently perform high-speed and flexible quality control of ammunition cases with different calibers and specifications, enabling the advancement of technological innovation in the sector.

This innovative approach should be recognized as a step toward raising quality, safety, and efficiency standards in ammunition case production and enhancing the global competitiveness of our defense industry.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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