LineFAME: A Design Method for a Lead-Free Bullet Production Line at the Weapons and Ammunition Factory of Peru

Edgar Alexis Rosas Espinoza, MSc[1]; Carlos Quinto Huamán, PhD[2]; Estrellita Cristal Ruiz Guevara, Eng[1]; Willian Bobadilla Saavedra, PhD[1] and Percy Fortunato Ochoa Castillo, PhD[1]
[1]Grupo de Investigación en Ciberseguridad, IoT e Inteligencia Artificial (GriCIA), Instituto Científico y Tecnológico del Ejército, Lima, Perú, *erosase@icte.edu.pe, eruizg@icte.edu.pe, sromerov@icte.edu.pe, wbobadillas@icte.edu.pe*
[2]Universidad Privada del Norte, Lima, Perú, *carlos.quinto@upn.pe*

Abstract*– Currently, the global defense industry faces the challenge of modernizing its production processes based on principles of environmental sustainability, operational efficiency, and personnel safety. In this context, many ammunition factories are adopting lead-free manufacturing models, in accordance with the Sustainable Development Goals (SDGs) and the technical requirements of international markets. This study is framed within that trend and presents LineFAME, a design model applied to the reengineering of the lead-free bullet production line at the Army Weapons and Ammunition Factory of Peru (FAMESAC). The project begins with a diagnosis of the current processes, which are characterized by intensive lead usage, a process-based functional layout, high operational times, dependence on imported inputs, and occupational health risks. The proposal is structured into two key phases. The first phase is oriented toward the acquisition of suitable raw material, specifically 90/10 brass bars, through in-house melting, extrusion, drawing, and heat treatment. The second phase focuses on configuring an efficient, continuous, and lead-free production line, installed in a single facility and based on a product-oriented layout. This new configuration made it possible to reduce the total manufacturing time from 29 to 17 hours, while also decreasing the amount of machinery, production waste, and personnel required. The results were validated through hardness testing, metallographic analysis, and field ballistics tests, as well as through a survey conducted with the technical and operational personnel of the Army Weapons and Ammunition Factory of Peru. The survey demonstrated a high level of acceptance regarding the implemented changes. In this way, LineFAME represents a viable and replicable alternative aligned with international standards for the modernization of ammunition production, ensuring efficiency, technological autonomy, and institutional sustainability.

***Keywords*– Lead-free ammunition, brass alloy, bullet production line, process optimization, military manufacturing, FAMESAC, sustainable defense.**

I. Introduction

The Ammunition Factory of the Army Armament Service of Peru (FAMESAC) currently maintains two main ammunition production lines: 7.62 × 51 mm and 9 × 19 mm calibers. This study focuses on the latter, whose production continues to follow a traditional model based on lead-core bullets. The process involves distinct stages carried out in specialized facilities, such as the lead plant, the manufacturing plant, and the brass plant, using raw materials acquired from external suppliers, including 90/10 brass strips and metallic lead. This process-based production structure entails frequent interplant transfers, prolonged operating times, and external dependencies that negatively affect costs and operational efficiency.

In a highly competitive international context, the price of a box of 50 cartridges in 9 mm caliber, manufactured by companies such as CBC (Brazil) or RWS (Germany), ranges from 21.80 to 24.85 USD. FAMESAC's ammunition is sold at approximately 23 USD per box, placing it within a competitive range. However, when considering the additional costs associated with importing foreign products, FAMESAC faces the challenge of maintaining high-quality standards while reducing costs to strengthen its competitiveness. Achieving this goal requires improvements in technical efficiency, reorganization of machinery layout under a product-based plant scheme, optimized use of raw materials, and the implementation of control systems that regulate critical variables such as weight, volume, temperature, cycle times, and equipment efficiency.

Since 2017, FAMESAC has been certified under ISO 9001:2008 for quality management by SGS Peru, reinforcing the need to apply rigorous controls throughout all phases of the production process. This certification requires strict compliance with quality protocols, evaluated through specific formats from material reception to the final product, ensuring the traceability and conformity of projectiles across different calibers. In this scenario, it is important to highlight that Peru is a producer of strategic industrial metals such as copper and zinc, which are used in the fabrication of components through alloys like CuZn30 (brass 70/30), also known as cartridge brass, due to its excellent malleability and ductility for manufacturing casings and bullets. However, the continued use of lead poses increasing challenges regarding environmental sustainability and occupational health.

In recent decades, developed countries and international manufacturers have directed their research toward the design and production of lead-free ammunition, a trend driven by regulatory demands and the pressure of global environmental standards [1]. In line with the Sustainable Development Goals (SDGs), the transition toward lead-free ammunition directly supports SDG 3 (Good Health and Well-being), by reducing personnel exposure to toxic materials; SDG 9 (Industry, Innovation, and Infrastructure), by promoting more efficient and innovative manufacturing processes; and SDG 13 (Climate Action), by minimizing environmental contamination resulting from the use of lead in military operations [2]. In this context, this article proposes the design of a new lead-free bullet production line for FAMESAC, aimed at enhancing operational sustainability, ensuring worker safety, and guaranteeing compliance with international environmental and technological quality standards.

This article is organized into six sections. The first is this introduction. Section II briefly outlines key concepts related to the ammunition manufacturing process. Section III presents related work on arms and ammunition production lines. Section IV details the proposed method, describing the two phases of implementation. Section V presents the results obtained. Finally, Section VI provides the conclusions of this study.

II. Lead-free ammunition manufacturing process

A. *Process improvement and cost reduction*

Any innovation in the production process necessarily involves continuous improvement. According to [3], process improvement begins with identifying a problem, analyzing it, and applying strategies that standardize and optimize internal activities, thereby improving quality, reducing costs, and increasing customer satisfaction. In the context of the lead-free bullet production line, continuous improvement is oriented toward material efficiency and the reorganization of machinery layout. In addition, [4] proposed scientific methods to reduce costs through time and motion studies, tool standardization, detailed planning, and efficient personnel selection. Today, these concepts are applied through inventory optimization, overhead control, and strategic outsourcing.

B. *Raw material and manufacturing inputs*

According to [5], raw material is the essential input in any industrial transformation process. In ammunition manufacturing, metals such as copper and zinc are commonly used to form brass alloys. The typical proportion in cartridge brass is CuZn30, composed of 70% copper and 30% zinc, which is ideal for cartridge cases due to its malleability and strength [6]. Brass 70/30 is mainly supplied in the form of bars, which are later transformed into components such as casings and bullets. Properties like thermal conductivity, corrosion resistance, and durability make it the optimal material for ballistic applications. Additionally, mechanical properties such as ductility, tensile strength, compressive strength, and malleability enable controlled deformation during drawing and forming processes.

C. *Plant layout and production line*

An ammunition production facility must be designed to ensure efficient material flow. Reference [7] distinguishes two main layout approaches: product layout and process layout. The product layout organizes machinery based on a linear product flow, making it ideal for high-volume, low-variability manufacturing (see Figure 1). The process layout groups similar operations together and is useful in environments with low production volume or customized products. According to [8], a production line consists of sequential stations where each operation partially transforms the raw material. Reference [9] adds that there are manufacturing lines, in which the product is gradually transformed, and assembly lines, where various components are put together. Flexible production lines have also become relevant, as they can adapt to demand changes without compromising efficiency.

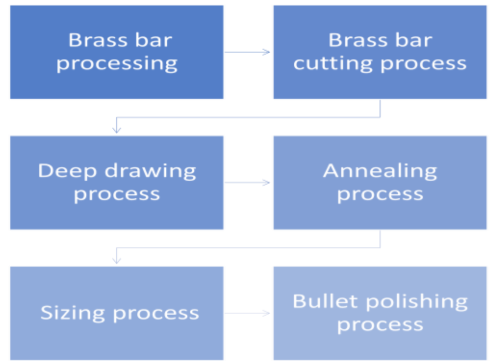

Fig. 1 Bullet manufacturing processes.

D. *Technical specifications and quality standards*

Every production system must follow standardized technical parameters. According to the State Procurement Supervisory Agency [10], technical specifications define the production, evaluation, and usage conditions of a product. These specifications ensure clarity, precision, consistency, and regulatory compliance. In the case of FAMESAC, these criteria are aligned with its ISO 9001:2008 certification, which establishes rigorous quality control procedures at all stages of the production process.

E. *The cartridge and its components*

A small-caliber cartridge (such as the 9x19 mm) is composed of four main elements: the case, the projectile, the gunpowder, and the primer. The bullet or projectile is typically made of lead or a lead alloy with a metallic jacket. In the proposed model, lead is replaced by alternative materials that maintain ballistic performance while reducing environmental impact and health risks for operational personnel [11]. Figure 2 shows the components of the ammunition.

Fig. 2 Ammunition components.

F. Relevant physical properties

The mechanical properties of metals used in ammunition manufacturing determine their behavior during processing. Ductility refers to the ability of a material to deform without breaking, which is essential for drawing processes. Malleability is related to the ability to deform under compression, crucial for cartridge case forming. Tensile and compressive strength are applied stresses used to evaluate the material's resistance during forming. The concept of "grains" is also relevant; it is a unit of mass traditionally used in ballistics. In this study, an 115-grain bullet is considered, equivalent to 7.5 grams, for calculations related to efficiency and raw material consumption [12].

III. State of the Art

In recent decades, the military industry has intensified its research efforts to design and manufacture safer, more efficient, and more sustainable ammunition. In developed countries, this trend is primarily driven by the need to reduce environmental pollution caused by toxic materials such as lead, protect the health of exposed personnel, and align industrial processes with the Sustainable Development Goals, particularly Goal 3 (Good Health and Well-being), Goal 9 (Industry, Innovation, and Infrastructure), and Goal 13 (Climate Action).

From a materials engineering perspective, one study examined the properties of brass UNSC 38500, aluminum UNSA906061, and bronze UNSC90700, concluding that thermal treatments such as annealing significantly improve the strength, hardness, and ductility of these materials [13]. These findings are especially relevant in the manufacturing of metallic ammunition components, where good formability without loss of structural integrity is required.

In terms of industrial process optimization, another study proposed the implementation of streamlined processes at the Santa Barbara State Company, dedicated to the production of weapons, ammunition, and armor [14]. Its integrative approach helped reduce costs, eliminate rework, and increase operational efficiency in the management of procurement, suppliers, and human resources. A study in Colombia suggested that improving quality and reducing costs should go hand in hand by analyzing operating conditions and controlling processing times [15]. This view aligns with another case in which Lean Manufacturing tools were applied to a 9×19 mm ammunition production line, achieving reductions in machine downtime, improvements in maintenance, and less reprocessing [16].

In the field of occupational health, several studies have examined the pulmonary toxicity of particles generated during firearm discharges [17]. The study revealed that metals such as lead, barium, and antimony, found in primers and projectiles, are highly harmful when inhaled, potentially causing acute damage to the respiratory tract and other organs. This scientific evidence reinforces the need to gradually eliminate lead from light weapon systems. Other studies have provided detailed descriptions of operational procedures for cartridge manufacturing, including the production of casings, bullets, tooling, and quality control [18]. A technical manual on 5.56×39 mm cartridges from Guatemala emphasized the importance of process standardization and proper machine setup to achieve production efficiency. In [19], the focus was on improving the production process of brass rods in a weapons and ammunition factory, demonstrating that staff experience, machinery maintenance, and the availability of measuring instruments directly influence cost reduction. This perspective is complemented by the research in [20], which highlighted the positive impact of a preventive maintenance program on productivity in ammunition manufacturing. In [21], the study addressed improvements in the physical organization of warehouses and work areas, as well as in the use of tooling, for 9 mm bullet and casing production lines. It concluded that optimizing space and controlling tooling reduces operational failures and enhances production performance. In [22], the implementation of a new casing production line in parallel with the existing machinery at FAMESAC was proposed. The study showed that the use of modern equipment not only reduces waste but also increases production capacity, thereby improving the competitiveness of the company. Taken together, the reviewed studies emphasize the importance of innovation in materials, efficiency in production processes, continuous improvement in industrial maintenance, and risk management for human health and the environment. This review provides a solid foundation for future technological developments in ammunition manufacturing, particularly those aimed at eliminating the use of lead in their composition.

IV. Proposed Method

This study proposes a design method for a lead-free bullet production line at the Army Weapons and Ammunition Factory. The method is structured in two main phases: (i) obtaining suitable raw material, which involves the selection, production, and technical verification of 90/10 brass (90 percent copper and 10 percent zinc), and (ii) configuring the operation of the production line, which involves organizing the technical and human resources necessary to execute the production process.

As a result, the process yields certified raw material ready for transformation, as well as a production line that is technically and operationally structured for the manufacture of lead-free bullets. The specific details of each phase are developed in the following sections. Figure 3 shows the phases of the proposed method.

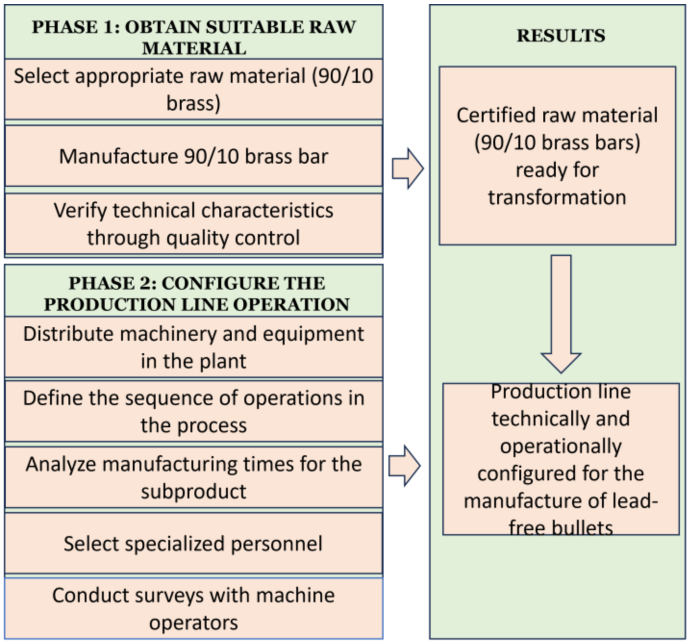

Fig. 3 Phases of the proposed method

A. Phase 1: Obtaining suitable raw material

To acquire optimal raw material for the production of lead-free bullets, three main activities were developed: selecting base materials, casting and forming, and verifying the technical characteristics of the intermediate product. Each stage is described below, based on procedures implemented at the FAMESAC brass plant.

A.1. Selecting suitable raw material

The base metals needed to produce the CuZn10 alloy (90/10 brass) were selected from the inputs stored by the Logistics Department. To achieve the correct proportion, materials were weighed using a calibrated electronic scale, applying a weight ratio of 900 kg of copper and 100 kg of zinc per 1,000 kg of mixture. This proportion ensures an alloy containing 90 percent copper and 10 percent zinc, as shown in Figure 4.

Fig. 4 Raw materials copper and zinc

A.2. Manufacturing 90/10 brass bar

The selected raw material was transported to the crucible furnace in the casting area of the brass plant (see Figure 5), where the melting process was conducted at 1,150 °C for a total of 9 hours, divided as follows: furnace heating (3 hours), loading and transport of raw material (1 hour), melting (2 hours), casting (1 hour), and cooling (2 hours).

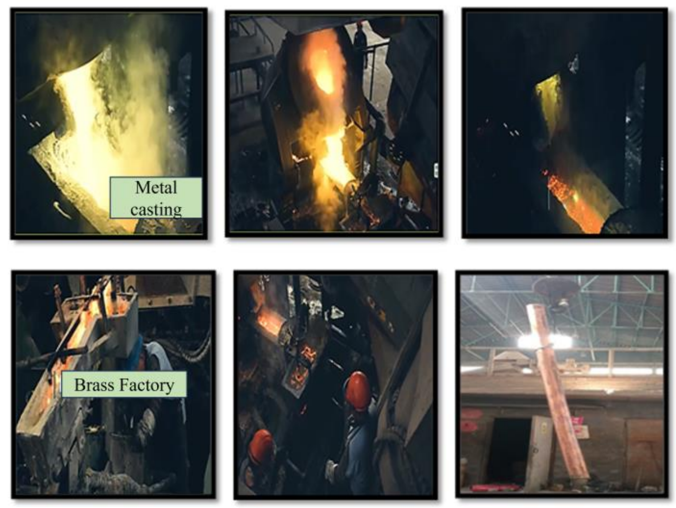

Fig. 5 Brass plant casting process

After casting, the continuous strand was cut into cylindrical billets using an "ORLANDI" mechanical saw, obtaining approximately 12 billets of 90/10 brass alloy with a diameter of 200 mm and a length of 380 mm per ton processed. For the extrusion process, the billets were heated to 750 °C for one and a half hours until reaching a red-hot state, as shown in Figure 6. They were then extruded toward a rotating container known as the cooling bank, forming coils with a diameter between 15.1 and 15.3 mm. These coils were then subjected to surface cleaning (pickling) in sulfuric acid (H_2SO_4) baths for 8 to 10 minutes each, totaling 1.5 hours for 12 coils. After cleaning, the coils underwent an annealing heat treatment at 550 °C for 5 hours to relieve internal stresses accumulated during coiling and diameter reduction.

Subsequently, the drawing process was carried out using a combined machine that integrated three operations: reduction, annealing, and drawing (see Figure 7). The material was processed through dies that reduced the diameter from 15.2 mm to 9 mm over a period of 9 hours. The time diagram summarizes ten processes, totaling 55 hours distributed over seven working days (see Figure 8). The process diagram illustrates a linear production line starting from the raw material dosing to the final 90/10 brass bar (see Figure 9).

Fig. 6 Billet cutting and extrusion into coils

Fig. 7 Combined drawing machine and reducing die

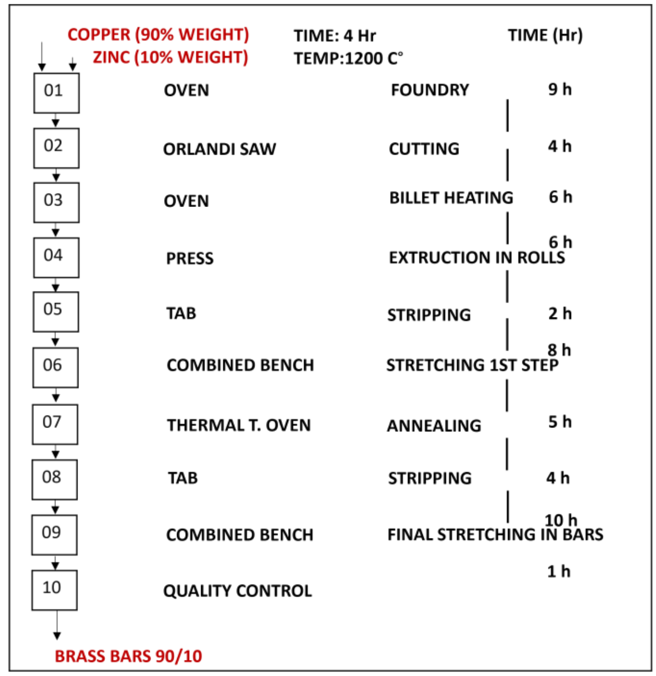

Fig. 8 Processing times for manufacturing the 90/10 brass bar

A.3. Verifying technical characteristics through quality control

During the continuous casting, a sample was taken to verify the chemical composition through technical analysis. To compensate for zinc loss due to evaporation (with a low melting point of 420 °C), an additional 2 to 3 kg was added to the process. A metallographic analysis was performed to determine the grain size of the alloy, which must be close to 35 microns to ensure resistance to cracking in later stages (see Figure 10). Finally, hardness was measured using a Vickers

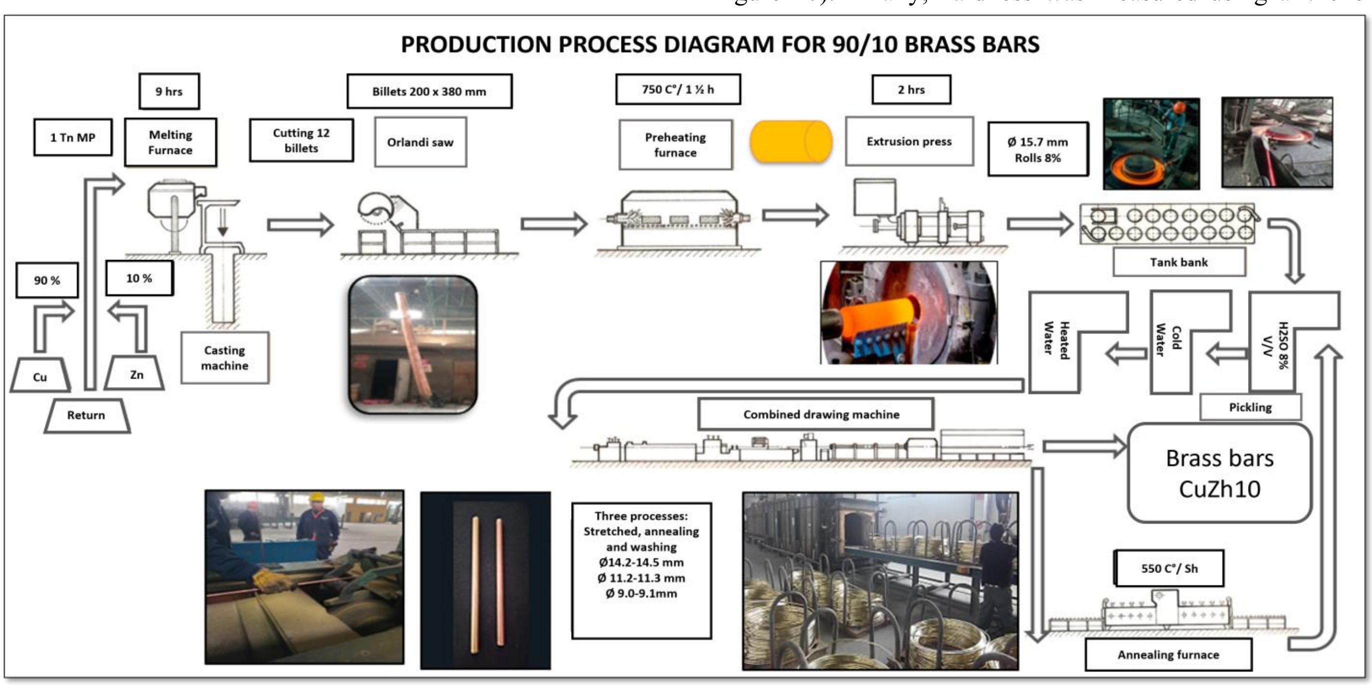

Fig. 9 Process diagram of the brass bar

hardness tester, yielding a value of 115 HV, which falls within the expected parameters as shown in Table 1. This ensures suitable conditions for subsequent transformation processes. The resulting bar meets the requirements to be used as the initial subproduct for lead-free bullet manufacturing. In this pilot project, two bars measuring 1,000 mm × 9 mm were produced, from which around 100 test units are expected to be manufactured at the ammunition plant.

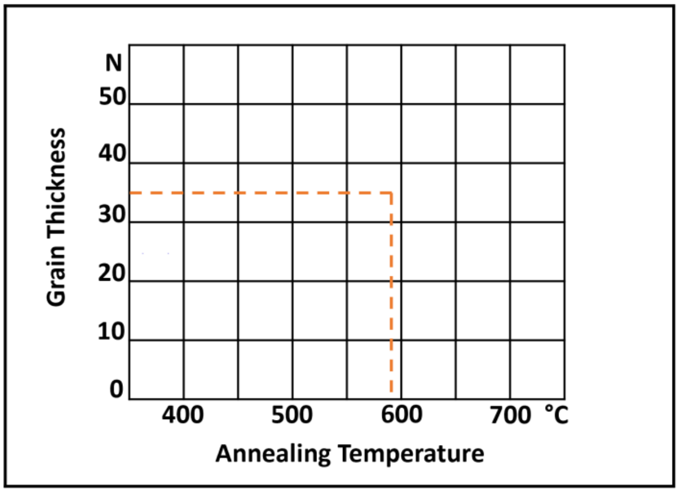

Fig. 10 Annealing temperature versus grain size of CuZn10

TABLE I
TECHNICAL SPECIFICATIONS OF THE PRODUCT – 90/10 BRASS BAR

Cu %	Zn %	Tensile Strength Limit (Kg.f/mm²)	Diameter Ø (mm)	Elongation % (mm)	**Hardness** (HB/HV)
89-91	9-11	28-42	9	10-48	60-120

A.4. Process justification in the brass plant

The implementation of the new 90/10 brass bar production process at the FAMESAC plant represents a significant technological and innovative advancement in the use of raw materials. The internal production of this subproduct, using specialized machinery, qualified personnel, and quality control instruments, eliminates dependence on external suppliers. This leads to reduced waste during production, cost savings in material acquisition, and improved use of resources available in the domestic market. This approach also opens the possibility of offering a new product to institutions such as the Army, Navy, Air Force, National Police of Peru, and shooting centers for military and civilian training.

As a comparison, in 2020, 90/10 brass strip was acquired from external suppliers at a cost of $74,819.68 for the production of one million projectiles. In contrast, the new model proposes purchasing raw materials for internal processing at a cost of $65,466.91, representing an approximate savings of 12.5 percent. It is important to note that since the start of its operations, FAMESAC has traditionally depended on external suppliers for brass strip. With this new process, independent production is consolidated at the plant, marking innovation in both product and process. The results obtained enabled the production of brass bars with a 90 percent copper and 10 percent zinc composition, meeting the technical specifications verified by the Quality Control Department. This subproduct is now ready to be used as input in the lead-free bullet production line, promoting technological, economic, social, and environmental development of the institution and generating a positive impact by introducing a new nationally produced product to the market.

B. Phase 2: Configuring the production line operation

B.1. Distributing machinery and equipment in the plant

The traditional layout for lead-core bullet production, implemented in the manufacturing and lead plants, follows a process-based design. In this model, 16 machines are operated in different work areas, each with its own operator and quality control personnel. This setup requires subproducts to be physically transported between sections of the plant after each process, leading to time losses, increased use of human resources, and cross-contamination risks, particularly from handling lead.

B.2. Defining the process operation sequence

The first subcomponent is the lead core, manufactured in the lead plant located 100 meters from the main production facility (see Figure 11). Once produced, this subcomponent is transported to the main plant. The second subcomponent is the Copabala or jacket, which is produced within the manufacturing plant but also requires movement between different areas. For the lead core, six machines are used, operated by two workers, and the process is distributed as follows: melting (1 hour), extrusion (1 hour), cutting and calibration (3 hours), degreasing and polishing (2 hours), and visual inspections (2 hours). The transfer of the core to the manufacturing plant takes an additional hour. In total, this subcomponent requires 10 hours of production. The process generates contamination due to lead handling, which affects not only the lead plant but also the manufacturing plant. Exposure to lead poses a health risk for workers and represents an environmental issue.

The second subcomponent, the Copabala, is produced through a ten-stage process using ten machines. Figure 12 shows the processes involving 90/10 brass strip, where the raw material is transformed and waste is generated. The process begins with the reception of the 90/10 brass strip (1 hour), followed by cutting and deep drawing (1 hour), which produces 30 percent scrap. Then, degreasing is carried out (2 hours), followed by heat treatment at 550 degrees Celsius (2 hours), cleaning with sulfuric acid and soap (1 hour), polishing (1 hour), visual inspection (1 hour), transport to assembly (1 hour), assembly with 14 dies (2 hours), and finishing processes including polishing, visual, dimensional and weight checks, and lotting. The total production time for the Copabala is 19 hours.

Together, the lead core (10 hours) and the Copabala (19 hours) require 29 hours to complete a lead-based bullet. Additionally, the process generates a total of 53.3 percent waste from the 90/10 brass strip, composed of 30 percent strip loss and 23.3 percent Copabala (ring) waste. This configuration involves more process steps, greater use of operators, inter-area transport, and exposure to hazardous materials.

To address the inefficiencies of the traditional process, a new production line for lead-free bullets was designed with reduced processing time and a linear product-based layout installed exclusively in the manufacturing plant. This new configuration is illustrated in Figure 13 through an operations diagram and consists of only nine machines, each operated individually. The process begins with the transfer of the 90/10 brass bar (1 hour) from the logistics warehouse to the PKE10 cutting and deep drawing machine, which uses a single die to directly shape the lead-free bullet (2 hours). This highly efficient operation does not produce significant scrap since any leftover material can be recycled through melting in the brass plant.

The production flow continues sequentially with polishing (1 hour), heat treatment (3 hours, with the furnace turned off during the final hour), chemical pickling with a sulfuric acid, detergent and water solution (0.5 hour), second polishing (1 hour), visual inspection (1 hour), calibration and forming in the PBM5 or PB31/14 machine using a single die (2 hours), another visual inspection (1 hour), dimensional verification (2 hours), weight control (1 hour), another round of polishing (1 hour), and finally, lotting (1 hour). This new sequence completes the process in 17 hours, which is 12 hours less than the traditional method, representing a 41 percent reduction in production time. It also brings multiple benefits, such as fewer machines, reduced staffing needs, elimination of lead use, and therefore, less contamination and lower dependence on external suppliers.

Moreover, the use of a single die instead of fourteen simplifies the assembly process and significantly reduces material waste. In this context, the implementation of the lead-free production line demonstrates comprehensive operational, environmental, economic, and technological improvements. Through the redesign of the plant and the effective use of existing resources, it has been possible to optimize workflow, reduce exposure to hazardous materials, and consolidate a cleaner, faster, and more sustainable manufacturing system.

Fig. 11 Lead core casting and forming process

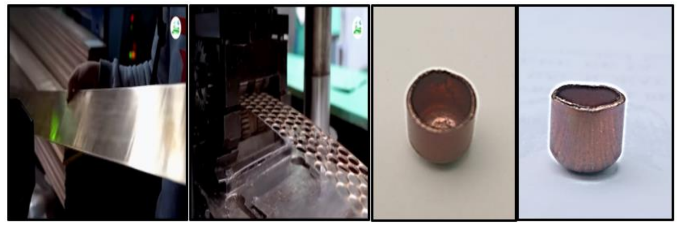

Fig. 12 Obtaining the transformed raw material and waste

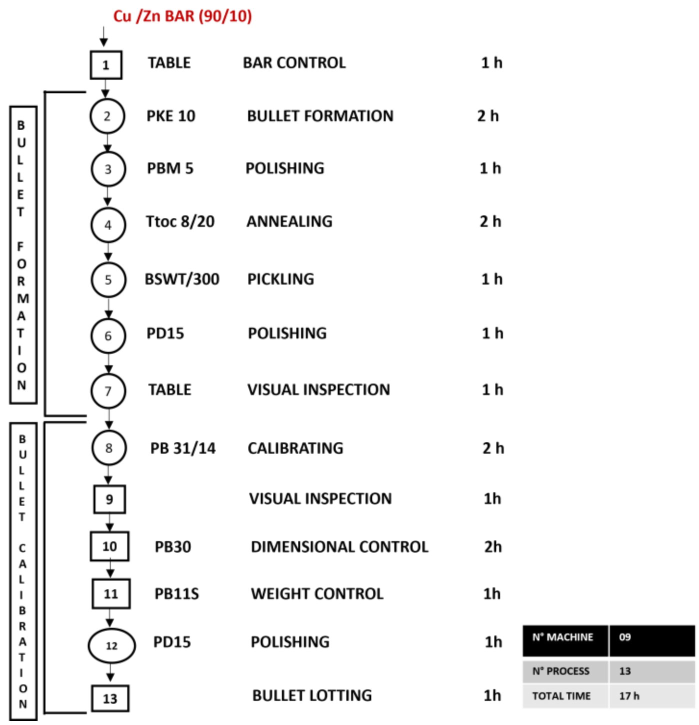

Fig. 13 Operation diagram and processing times of lead-free bullet

B.3. Analysis of subcomponent manufacturing times

When comparing the new product-based plant configuration with the traditional process-based layout, there is a substantial improvement in operational efficiency. The lead-free bullet production line, developed entirely within a single facility using a linear arrangement, completes the process in 17 hours compared to the 29 hours required by the traditional system. This 12-hour reduction represents a 41 percent savings in production time, indicating a significant improvement in productivity and a decrease in operational costs.

Figure 14 shows the lead-free bullet forming machine, equipped with a single die, which simplifies the process compared to the traditional assembly that requires 14 dies.

Fig. 14 Lead-free bullet forming machine equipped with a single die

B.4. Selection of specialized personnel and survey application

To ensure the successful implementation of the new process, a Likert-type survey was administered to 30 workers including operators and supervisors from both the brass plant and the manufacturing plant. The personnel involved in the development of this project at FAMESAC included a production supervisor, quality control staff, manufacturing machine operators, tooling machine operators, casting machine operator, and cartridge assembly operator. This group of professionals, through their experience and technical expertise, along with the survey results, supports the technical, economic, social, and environmental feasibility of implementing the new lead-free bullet production line.

V. RESULTS

A. Results

A.1 Brass Plant

The experiments carried out at the brass plant aimed to produce 90/10 brass bars composed of 90 percent copper and 10 percent zinc through three main processes: casting, extrusion, and drawing. This experimental work made it possible to obtain a raw material with the proper mechanical properties for the subsequent compression steps required in the production of lead-free bullets. During casting, the metals were melted to form a homogeneous alloy while ensuring that the resulting Vickers hardness (HV) stayed within the optimal range for compression processes, between 60 and 120 HV, as shown in Table 1. The tests achieved a hardness value of 115 HV, validated by the quality control department and equivalent to 115 HB on the Brinell scale, which falls within the desired range to guarantee the malleability of the material during bullet shaping. After casting, the bar was extruded using a tungsten steel die with a diameter of 200 millimeters, resistant to both friction and high temperatures, reducing the material to a diameter of 18 millimeters. In the next stage, the drawing process continued reducing the bar to a final diameter of 9 millimeters using smaller conical dies measuring 99 millimeters. These dies were heat treated to withstand frictional wear. Annealing treatments were applied between the diameter reduction steps to relieve internal stresses and avoid excessive increases in hardness, keeping it below the brittleness threshold. This sequence of operations enabled FAME SAC, for the first time in its history, to produce 90/10 brass bars internally, eliminating the traditional reliance on external suppliers.

A.2 Manufacturing Plant

Once the 90/10 brass bars were processed at the manufacturing plant, the production of lead-free bullets began. Unlike the traditional method of jacketed lead cores using brass strips, this process starts with a solid brass bar that is compressed by deep drawing and stamping to form the projectile. This significant difference also shifts the mechanical property requirements, emphasizing compressive strength rather than ductility.

The process began by cutting the bar into slugs measuring 9 by 13.2 millimeters, equivalent to 115 grains or 7.5 grams, using the grinding machine located in the tooling and maintenance area. The slugs were then shaped on the PBM5 forming and sizing machine, which gave each projectile its final aerodynamic profile. Firing range and ballistic lab tests confirmed excellent grouping and projectile accuracy without deviations, as shown in Figure 15. These results validate the effectiveness of both the design and the materials used. Furthermore, it was confirmed that despite a slightly longer length due to the absence of lead, the bullet does not affect the powder charge or ballistic performance and remains within the tolerances defined by MIL-C 70509 AR.

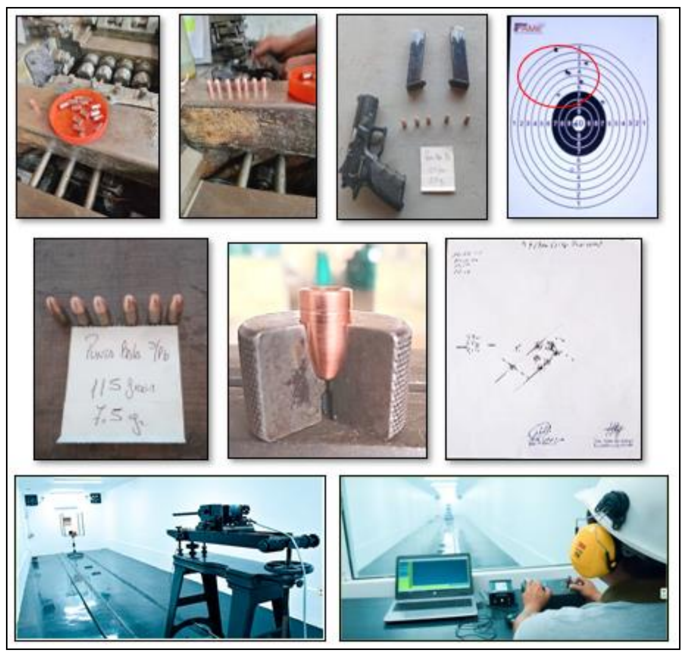

Fig. 15 Precision in grouping in field and laboratory

A.3 Validation of Survey Results

Figure 16 shows the percentage distribution of responses on a Likert scale (values from 1 to 5) for each of the twelve questions in the survey administered to personnel involved in the production process. A clear concentration of responses is observed in levels 4 and 5, corresponding to agree and strongly agree, which reflects a positive attitude and acceptance toward the proposed changes in the lead-free bullet production line. The questions with the highest level of consensus were Q2 (knowledge of material properties), Q6 (use of technology in the material), and Q12 (relocation with training), all of which received 100 percent of responses in the top two levels of the scale. This indicates unanimous understanding of the technical aspects of the change and a willingness to actively participate in its implementation. These were followed by Q1 (importance of training), Q4 (knowledge of alternative processes), and Q5 (optimization through machinery redistribution), with 96.7 percent of positive responses, indicating strong appreciation for the role of training and operational improvements that support the technological transition. In the case of Q3 (risks of toxic materials) and Q8 (function rotation with training), 93.3 percent of respondents expressed agreement, reaffirming interest in a healthier and more flexible work environment. In contrast, though in lower proportion, Q7 (adaptation to new technologies) and Q11 (feasibility of lead-free production) had the lowest agreement rates at 83.3 percent. This may indicate specific areas where some workers still have doubts or lack information, suggesting the need for technical demonstration strategies and hands-on awareness initiatives.

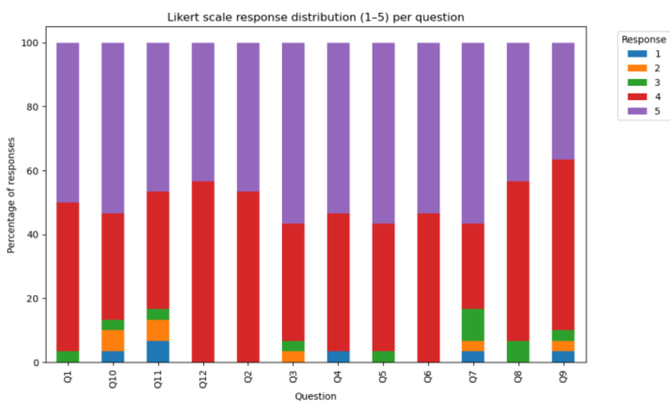

Fig. 16 Distribution of Likert scale responses 1 to 5 by question

Figure 17 complements the analysis by showing, for each question, the average response (blue bars), the standard deviation (black error lines), and the agreement percentage (responses of 4 or 5) represented by a green dotted line. This approach allows for the observation not only of the level of acceptance but also of the degree of consensus among respondents. Regarding averages, all items exceed the value of 4.0, with peaks in Q5 (machinery redistribution) and Q6 (technology in the material), both reaching an average of 4.53. This reflects a highly favorable and consistent perception of the proposed production and technological improvements. These items also show low standard deviations (0.57 and 0.50 respectively), indicating strong agreement among participants. The highest standard deviations appear in Q11 (feasibility of lead-free production) and Q10 (product-oriented plant model), both with values above 1.0, suggesting greater variability in opinions, possibly due to differences in technical training or direct experience with those aspects. Nevertheless, the averages for these questions (4.10 and 4.26 respectively) remain above the acceptance threshold. Finally, the combined analysis reveals that although there is majority acceptance, the presence of deviations in certain questions suggests that the implementation of change should be accompanied by reinforcement measures such as specialized technical training modules, guided tours of the new plant, and participatory spaces where staff can raise concerns and contribute suggestions.

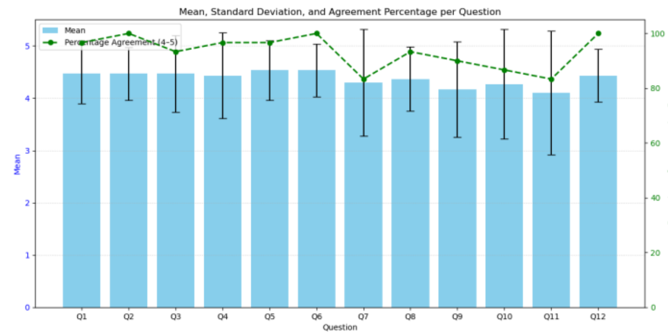

Fig. 17 Average, standard deviation, and agreement percentage by question

VI. Conclusions

The redesign of the bullet production line at the Army Weapons and Ammunition Factory (FAMESAC), through the implementation of the LineFAME model, demonstrated that it is feasible to modernize complex industrial processes by applying principles of efficiency, sustainability, and technological autonomy. The proposal went beyond simply replacing lead with less polluting materials; it addressed the entire production system in an integrated manner, from the procurement of raw materials (90/10 brass) to the final transformation of the projectile. This approach enabled the configuration of an industrial model more aligned with current defense sector demands and global environmental policies.

The results confirmed that the new design reduced the total manufacturing time of each projectile from 29 to 17 hours, representing a 41 percent improvement in operational efficiency. This change was made possible by eliminating redundant processes, reducing the number of required machines, implementing a product-oriented model, and using a single forming die for the lead-free bullet instead of the fourteen dies used previously. Additionally, the spatial reorganization of the line into a single plant generated logistical and safety benefits, optimizing space usage, human resources, and technical supervision.

From a technical perspective, the new projectile was successfully validated through metallographic tests, hardness measurements, and live ballistic trials, which confirmed its compatibility with existing weaponry and its satisfactory operational performance. Moreover, the internal manufacturing of raw materials (brass bars) ensures independence from external suppliers, reduces import costs, and strengthens the industrial capabilities of the Peruvian Army to adapt to potential logistical restrictions or crisis scenarios. This process also presents an opportunity to enhance the value of technical personnel and promote applied research within FAMESAC facilities.

Finally, the acceptance of the model by technical and operational personnel was a decisive factor in the feasibility of the transition. Surveys conducted showed a broadly positive perception, highlighting improvements in working conditions, reduced exposure to toxic materials such as lead, lower complexity in machinery usage, and recognition of the strategic value of the new system. In this regard, LineFAME represents not only an efficient and functional solution but also a significant step toward a more sustainable, safe, and technologically independent military production system, aligned with international standards and offering a replicable model for other defense units in the country or region.

ACKNOWLEDGMENTS

The authors extend their gratitude to the Cybersecurity, IoT, and Artificial Intelligence Research Group (GriCIA) of the Army Scientific and Technological Institute (Instituto Científico y Tecnológico del Ejército) and the Directorate of this university for funding the project.

REFERENCES

[1] United Nations Regional Centre for Peace, Disarmament and Development in Latin America and the Caribbean (UNLIREC), *Marco normativo mundial sobre la munición: una guía práctica para los Estados*. Lima, Perú: UNLIREC, 2022. [En línea]. Disponible en: https://unlirec.org/wp-content/uploads/ESP_Working-Paper_Global-Framework-Ammunition_Full.pdf

[2] Geneva International Centre for Humanitarian Demining (GICHD), *Underwater Explosive Ordnance: A Guide for Operational Response*, 1st ed., Geneva, Switzerland: GICHD, 2025. [En línea]. Disponible en: https://www.gichd.org/fileadmin/user_upload/GICHD_Underwater_EO_23052025_WEB.pdf

[3] Imai, M (1986), La clave del éxito competitivo de Japón. https://blog.valitrenta.com/kaizen-el-principio-de-la-mejora-continua/

[4] Taylor, F. (1911). Los Principios de la Administración Científica https://acortar.link/wOTRJj

[5] Ramírez, C. (2010). Fundamentos y técnicas de costos. https://acortar.link/wOTRJj

[6] Riba, R. (2008). Selección de materiales y diseño de máquinas. https://acortar.link/8F2Ea8

[7] De la Fuente y Fernández. (2005). "Distribución en planta" Universidad de Oviedo. https://acortar.link/UEIRqS

[8] Mira, J (2022) Línea de producción: Cómo aumentar la productividad y la calidad. https://acortar.link/o5jw3x

[9] García, (2020), "Línea de producción", Universidad Politécnica de Valencia. https://riunet.upv.es/handle/10251/138801

[10] OSCE, (2012). Instructivo para formulación de Especificaciones Técnicas para la Contratación de Bienes y Términos de Referencia para la Contratación de Servicios y Consultorías en General. https://acortar.link/A90EC9

[11] LP Derecho, "¿Cuáles son las partes de una munición, pistola y revólver?", LP Derecho, 29-May-2022. [En línea]. Disponible en: https://lpderecho.pe/partes-municion-pistola-revolver/ [Accedido: 08-jul-2025].

[12] Grizzly Cartridge, "What Does the Grain of a Bullet Mean?", Grizzly Cartridge, [En línea]. Disponible en: https://grizzlycartridge.com/what-does-the-grain-of-a-bullet-mean/. [Accedido: 08-jul-2025]

[13] Cújar, J. y De Oro, J., (2018). "Microestructura y Propiedades Mecánicas del Latón UNSC 38500, Aluminio UNSA906061 y del Bronce UNSC90700". Repositorio institucional de la Universidad de Córdoba-Colombia https://repositorio.unicordoba.edu.co/handle/ucordoba/686

[14] Sandoya, J., Vinicio, A., López, N., y Aníbal, A., (2018). "Implementación del proceso racionalizado en producción de armas, municiones, mecanizados y blindajes" de la empresa pública Santa Bárbara en el área de armas y municiones. http://repositorio.espe.edu.ec/handle/21000/14229

[15] Gonzales, E., (2014) "Propuesta para el mejoramiento de los procesos productivos de la empresa SEVIOPTICA LTDA", Pontificia Universidad Javeriana de Bogotá – Facultad de Ingeniería, Colombia. Repositorio Institucional la Pontificia Universidad Javeriana-Colombia. http://hdl.handle.net/10554/7118

[16] Benavides, D. y Alexander, A. (2018) "Análisis y propuesta de mejoras en una línea de producción de municiones 9x19 mm de una fábrica de armas y municiones, aplicando herramientas de Lean Manufacturing". Repositorio de Tesis PUCP http://hdl.handle.net/20.500.12404/12013

[17] Kim, YH., Vance, SA., Aurell, J., Holder, AL., Pancras, JP., Gullet, B., Gavett, SH., Mcnesby, KL. y Gilmour, MI. (2022). Química y toxicidad pulmonar de las partículas emitidas por armas de fuego. https://www.nature.com/articles/s41598-022-24856-5

[18] Ochaeta, O. (2010). "Manual de procesos para la fabricación de cartuchos calibre 5.56 x 39 mm en la fábrica de municiones del ejército de Guatemala". https://acortar.link/Oo9AdO

[19] Ochoa, P. (2021) "Mejoramiento del proceso productivo de barras de latón y su incidencia en la reducción de costos". Caso: Fábrica de Armas y Municiones del Ejército SAC, Lima 2018 – 2019 Repositorio del Instituto Científico y Tecnológico del Ejército http://repositorio.icte.ejercito.mil.pe/handle/ICTE/176

[20] Arévalo, F. (2017). "Mantenimiento y su influencia en la productividad del área de fabricación de municiones de una empresa militar". https://acortar.link/iiNieq

[21] Del Carmen, W. (2021). "Propuesta de mejora en las líneas de casquillos y balas de 9 mm en la planta de fabricación de la empresa FAME S.A.C". https://repositorio.ulima.edu.pe/handle/20.500.12724/8445

[22] Clemente, W (2021) "Implementación de una línea de producción de fabricación de casquillos de munición para incrementar la capacidad productiva en la empresa FAMESAC https://acortar.link/cUY5dV