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ORIGINAL

Implementation of Industry 4.0 in metallurgical factories

Implementación de la Industria 4.0 en fábricas metalúrgicas

Luz Tobar Subía[1], Cristian Tasiguano Pozo[2], Fernando Valencia[1], David Villarreal[1], Christian Vásquez[3], Guillermo Mosquera Canchingre[4]

[1]Universidad Técnica del Norte, Mechatronics Engineering Career. Ibarra, Ecuador.
[2]Instituto Superior Tecnológico San Antonio, Research and Publishing Department. Quito, Ecuador.
[3]Steelworxec. Quito, Ecuador.
[4]Universidad Internacional del Ecuador UIDE. Quito, Ecuador.

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Corresponding author: Luz Tobar Subía

ABSTRACT

This paper presents the preliminary results of a study on implementing Industry 4.0 in metallurgical factories. It showed that adopting Industry 4.0 technologies generates a productive environment characterized by real-time sensing, with high adaptability, flexibility, self-learning capacity, and fault tolerance. In the context of the Ecuadorian industry, particularly in micro, small, and medium-sized enterprises (MSMEs), there is limited integration of industrial technologies, both at the software and hardware levels. Additionally, many factories do not perceive the relevance of implementing solutions based on Industry 4.0 in key areas such as production, quality control, and maintenance. The study presents three case studies of metalworking factories that emerged as small locksmith workshops and analyzes the challenges related to incorporating new know-how in these industries. The findings concluded that Industry 4.0 has transformative potential for the value chain, facilitating the development of innovative products and services.

Keywords: Industrial Adaptability; Metallurgical Factory; Industry 4.0; Technological Integration; Digital Transformation; Real-Time.

RESUMEN

El presente trabajo presenta los resultados preliminares de un estudio sobre la implementación de la Industria 4.0 en fábricas metalúrgicas. Se demostró que la adopción de tecnologías propias de la Industria 4.0 genera un entorno productivo caracterizado por la sensorización en tiempo real, con alta adaptabilidad, flexibilidad, capacidad de autoaprendizaje y tolerancia a fallos. En el contexto de la industria ecuatoriana, particularmente en micro, pequeñas y medianas empresas (MIPYME), se evidenció una limitada integración de tecnologías industriales, tanto a nivel de software como de hardware. Adicionalmente, muchas fábricas no perciben la relevancia de implementar soluciones basadas en Industria 4.0 en áreas clave como la producción, control de calidad y mantenimiento. El estudio presenta tres casos prácticos de fábricas metalúrgicas que surgieron como pequeños talleres de cerrajería y analizó los desafíos relacionados con la incorporación de nuevos conocimientos técnicos en estas industrias. Los hallazgos concluyeron que la Industria 4.0 tiene un potencial transformador para la cadena de valor, facilitando el desarrollo de productos y servicios innovadores.

Palabras clave: Adaptabilidad Industrial; Fábrica Metalúrgica; Industria 4.0; Integración Tecnológica; Transformación Digital; Tiempo Real.

INTRODUCTION

A predominant characteristic in most Ecuadorian factories, particularly in micro, small, and medium-sized enterprises (MSMEs), is the scarce or non-existent integration of advanced industrial technologies, both at the software and hardware levels. The implementation of Industry 4.0 offers a production environment based on real-time sensorization, with high adaptability, flexibility, self-learning capacity, and fault tolerance. This process is facilitated using information technologies, databases, and the integration of sensors with technologies such as IO-Link.

While business automation is critical to improving competitiveness, one of the biggest challenges is the fear of failure on the part of managers, who are reluctant to invest in machinery, infrastructure, or research.(1) As a result, many factories do not perceive the relevance of Industry 4.0 in key areas such as production, quality control, and maintenance. However, investment in these technologies could generate short-term returns, optimize processes, and improve product quality.

In the visits to the companies studied it was observed that none had a preventive maintenance program, much less procedures to develop predictive maintenance plans that ensure the optimal performance of critical equipment. In addition, many small and medium-sized enterprises lack a clear organizational structure, as roles within organizations, often family-owned, are not defined and staff are not always properly trained.

Another challenge is the lack of process analysis and installed capacity, which can lead to declining sales below breakeven. The lack of innovation is also a key factor in the stagnation and closure of many companies, as they tend to keep their processes and products unchanged, becoming obsolete without investing in research or new projects.

The Ecuadorian regulatory framework aggravates this situation by requiring the payment of all debts in the event of bankruptcy before the company can opt for other recovery alternatives. In Latin America, sources of financing are limited to banks with high interest rates, forcing entrepreneurs to mortgage their assets, assuming high risks.(2)

A possible solution to this crisis lies in the industrialization of small businesses and the promotion of an innovation environment that removes bureaucratic barriers and provides investment capital instead of borrowing.(3) This problem is not unique to Ecuador; Most Latin American countries face similar difficulties when trying to implement advanced technologies. A study carried out in Mexico highlights the need to adopt Industry 4.0 technologies to improve the competitiveness of SMEs and emphasizes the importance of having specialized personnel.(4)

Another research analyzes the current challenges of social security and emphasizes social insurance in Latin America in the face of Industry 4.0, based in Mexico.(5) For example, workers must accept and adapt to this new technology; In developed countries, this would seem easy, but in developing countries, the transition stage is affected by several reasons. One, the workforce is elderly and unfamiliar with available technologies. Two, the general population is male, whose age ranges from 41 years old and with an incomplete level of primary education. Three, 91 % of the population works in the operational area.(6)

This empowerment of technology involves academia as it includes opportunities for research, training, entrepreneurship, and innovation, providing a foundation for improvements around the world of Industry 4.0.(7) When talking about Industry 4.0 in Ecuador, many questions arise such as: what is Industry 4.0? is it applicable to the reality of Ecuadorian industry? This is one of the questions analyzed in the research. Academia plays a crucial role in this process, providing opportunities for research, training, and entrepreneurship, thus contributing to the advancement of Industry 4.0 at a global level. Despite the advances, in Ecuador the implementation of Industry 4.0 remains limited, restricted mainly to theoretical studies promoted by the university environment.(8,9)

The objective of this work is to implement Industry 4.0 technologies through applied research in the metallurgical industry of the northern part of the country, to increase the level of automation and generate substantial improvements in production.

This article is organized as follows: section 2 reviews the state of the art of Industry 4.0; Section 3 describes the companies that participated in the implementation of these technologies; Section 4 details the methodological proposal; Section 5 presents the results of the case studies; and finally, section 6 sets out the conclusions derived from the research.

State of the art

Industry 4.0

The term ''Industry 4.0'' was first used at the Hannover Messe in 2011, where it was proposed as part of Germany's High-Tech Strategy for 2020.(10) Driven primarily by research into information technology and cyber-physical systems (CPS).(11,12) Industry 4.0, the Industrial Internet, or Smart Factory is characterized by having all processes interconnected through the Internet.(13) It transforms all important business processes and realigns product and service portfolios, through external control of the Internet of Things (IoT).(14) The potential uses go far beyond the optimization of manufacturing techniques and their implementation, it also requires considerable investment.[15]

The industry is now equipped with multiple sensors and actuators that are networked for information exchange. The development of these sensors and actuators allows machines to store and analyze data in real-time, generating a database that will later be used for predictive analysis.

One of the advantages of Industry 4.0 is the implementation of smart sensors that generate data and information that go beyond conventional switching signals or measured process parameters. These elements use the IO-Link communication protocol.[11,16] That is why smart sensors receive commands and parameter data directly from the controller and, as a result, are constantly adapted to new requirements. This allows them to create substantial increases in efficiency, flexibility, and better planning security for preventive maintenance of the system.

One of the disadvantages of Industry 4.0 is the level of security and access control to the system that each manager has, with the greatest concern being the hacking of information stored in the cloud.[17] Currently, this issue is in the stages of research and testing; safety protocols have yet to be defined. Because of this, there is little availability in technology stores of this equipment (sensors and actuators).

Currently, there are research projects that develop electronic components, sensors, and signal processing methods capable of detecting: component wear due to operating noise, abnormalities, or failures in the production process more easily and reliably than in the past; for example, using acoustic event detection methods.[18,19]

Henning B 2006 seeks to develop a highly autonomous and wirelessly integrated energy sensor platform in industrial facilities.[20] This technology will be tested in quality control in semiconductor production and the detection of failures in axial piston pumps.

The fields of application of Industry 4.0 in the country are many, from medical technology to the automotive industry. For example, in medical technology, there is a closer relationship with the patient and direct and less offensive treatments.[21]

Industry 4.0 in Latin America

The Fourth Industrial Revolution has been efficiently applied in some Latin American countries. Such is the case of Mexico, where several measures have been incorporated to bring Industry 4.0 to the country's factories. Some of the measures used have been the creation of a technological roadmap, programs for the dissemination of new technologies, the creation of innovation and technology centers, and training of the workforce.[4] One of the examples of the successes of the incorporation of Industry 4.0 is that of several shoe companies in Guanajuato, where thanks to the support provided by the Innovation and Design Center of the Chamber of the Footwear Industry of Guanajuato, it was possible to increase national exports by 16,42 % in 2017. Another example is that of the medical publishing company Para Los Médicos (PLM), which avoided closing thanks to the incorporation of IBM's Watson Content Analytics technology, which is based on artificial intelligence. As a result, PLM had more than 17 million virtual consultations in 2015.[22]

On the other hand, in Brazil, some technologies have already been applied in their production systems, in such a way that modern management systems have been implemented and advances have been made in automation, robotics, mobile communication, sensors and actuators.[23] Despite this, efforts to take the current industry to a higher level still need to be increased. Some examples of the incorporation of the technologies of the fourth industrial revolution are the ThyssenKrupp auto parts unit, located in Poços de Caldas; and the company Vale, which is based in Rio de Janeiro. Compared to the first company, the waste rate has been reduced and production has increased. This unit can produce 700 thousand modules annually with only 72 workers, which is a great advance since it is estimated that without the technology implemented, around 200 workers would be needed. Now, concerning the second company, it saved US$ 50,5 million through the digitization of processes and work with artificial intelligence.[24]

Finally, in Colombia, there are several manufacturing plants, which were created about 20 years ago, which has caused their processes to be outdated. Specifically in Bogotá, there is a low level of adoption of Industry 4.0 technologies in companies and factories. 85 % of manufacturing SMEs do not carry out any type of training regarding these technologies. In addition, only 2l 18,6 % have an investment plan in this type of element. 60 % do not work with any cloud computing tool, and only 3,9 % use a computer program focused on data processing. Even in the government, there is a high lag in several elements of this new type of industry. Only 3,3 % of official entities have the conditions to venture into Big Data.[25,26]

METHOD

The research focuses on improving processes in three metallurgical companies in northern Ecuador. During the study, failures and bottlenecks were identified, which allowed technological solutions to be proposed to increase automation and optimize production significantly, to achieve concrete improvements in industrial operations.

Metallurgical factories

In the study carried out on three factories in the metallurgical sector, industry 4.0 was implemented in the maintenance area, being a vulnerable sector, because corrective maintenance was the only one used by the companies.[27] When corrective maintenance is carried out in most cases, the most critical components are affected, causing the cost of maintenance and downtime to be prolonged, delaying production.

The implementation of Industry 4.0 in maintenance allows significant progress to be made by focusing on the optimization of critical machinery. This is achieved through vibration control, fault monitoring, the implementation of redundant sensors and instruments, and the use of advanced technologies such as thermography and ultrasound. These tools facilitate the transition to predictive maintenance, which, through database analysis, allows the replacement of components to be anticipated, as well as to schedule and adjust maintenance activities, which reduces cost overruns, minimizes corrective maintenance, and reduces production downtime.

To ensure that equipment and facilities operate according to their design specifications, preventive and predictive maintenance plans were reviewed, as well as usage schedules defined by production requirements. An exhaustive survey of information on the equipment in the plant was carried out, identifying its technical characteristics and evaluating the current state of the machinery. Each piece of equipment was assigned a unique code, and a resume was generated that included its logbook, failure history, and a detailed preventive maintenance plan.

The three factories in which the research was implemented are described below. At their request, their names will be kept private. It is worth mentioning that all are located in the north of the country.

Factory 1

The creation of the company stems from the need of the local market. It was established in 1990 as a small locksmith workshop. Due to the increase in demand in 1998, it changed its location to a larger space with better equipment. In 2004 it began new projects for the design and casting of metals such as cast iron, bronze, and aluminum. The main products and services are:

- Casting of all kinds of parts of gray iron, bronze, and aluminum.
- Manufacture of all types of metalworking elements.
- Design and manufacture of machinery according to the needs of customers.

It is found that the process that causes bottlenecks is melting since the temperature of the cauldron is not a controlled variable.[28] This variable is measured empirically and using only a sensor, causing the material not to melt completely and the heating time is exceeded, generating unnecessary costs, breakdowns in the cauldron and material leaks sometimes. For this reason, it is proposed to control the melting temperature, with the installation of a redundant sensor for subsequent analysis of patterns, and thus give a prediction on the periodic maintenance of the instruments that will be used in the future.

Factory 2

It is dedicated to building and rebuilding agricultural and industrial machinery. Among its services are the maintenance of pumping stations for drinking water, changes of bearing boxes, alignment of pumps, construction of bases for elastomers of all sizes, and other services.

The main cause of economic losses in the company is the unexpected stoppage in the machines of the different production lines (machining, welding, and cutting) due to the absence of a maintenance plan within the company. The company, in the face of industrial development, has seen the need to create strategies to improve the lifetime of the machinery since it does not have a preventive-predictive maintenance program, so it is considering the implementation of a vibration control sensor in its most critical equipment, trying to identify patterns to predict the replacement of parts associated with the rotation train.

Factory 3

It was born 30 years ago as a locksmith's shop, building doors and windows; Later, the company received agricultural machinery work, such as maintenance and repair. That is the starting point from where agro-industrial machinery begins to be made. Later, industrial machinery began to be made for mining together with the food sector. Currently, the company is engaged in the design, manufacture, and assembly of industrial machinery and equipment, mechanical projects, and precision manufacturing. Its products are machinery and equipment for the construction, agribusiness, mining, and industrial sectors.

In this case, it is proposed to carry out a preventive maintenance program through the periodic review of the equipment, to detect failures before they happen and extend the useful life of the machine by applying industry 4.0.

Development

The implementation proposal for each of the companies, based on Industry 4.0, is presented below.

Industry 4.0 implementation plan

As is well known, Industry 4.0 is about a transformation towards the digitalization of the production system and represents a qualitative leap in the organization and management of the value chain, where commercial and production relationships entail a constant connection between customer, supplier, distributor, logistics, and manufacturer.

In Factory 1, the K-thermocouple type industrial temperature sensor was selected due to its wide operating range. This sensor is not installed directly in the furnace but in the crucible housing. Internal temperature values shall be determined by heat transfer calculations. The data collected will be sent to a database through a GSM HERMES LC-2 remote control system, allowing them to be viewed through a mobile application designed for this purpose.

In Factory 2, after identifying the critical process, a thorough analysis was carried out to select the appropriate technology, establishing a direct link with Industry 4.0. A remote system was designed to measure the critical variable and compare it with standard values. The implementation will serve to evaluate performance and perform vibration analysis, following the guidelines of the ISO 10816-1 standard, which classifies the condition of the machine according to its size.[29] The tests carried out on the Codim lathe were carried out using a vibration sensor with measurements made every hour.

In factory 3, considering the structure of critical equipment and the availability of predictive maintenance services in the city and the country, it was decided to implement an hour meter along with the development of a mobile application to record failures efficiently. A key example is the hydraulic bending machine, which requires a statistical failure analysis to implement preventive actions. Using a DS1302 RTC module, an Arduino Uno, an HC-05 Bluetooth module, and other mechatronic components, the hour meter was designed. Its main function is to alert to a failure, record the date and time, store the possible causes, and upload the information to the cloud, where the data will be analyzed to generate patterns and make informed decisions.

RESULTS AND DISCUSSION

This section presents an analysis of the preliminary results of the implementation of Industry 4.0, highlighting that industrialization in small businesses allows the generation of a database of the operation of main equipment, as well as the creation of failure histories, operability histories of production equipment and operating manuals with an interdisciplinary approach, in order to have greater availability, organization of information, planning of preventive and predictive maintenance, and reliability of equipment operation, in such a way that it can contribute to the improvement of the factory.

Factory 1

Due to the sociocultural context of the company owners, it was only possible to work with a minimum sample: 9 samples for data collection of the type K thermocouple. The millivolt (mV) output of the temperature sensor is controlled by a PID. Figure 1 details the minimum and maximum measurement range of 0,039 mV and 29,464 mV, which represents the temperature variation from 0ºC to 700ºC. The the sensor output is linear and establishes a pattern that allows the operator to identify the condition of the instrument inside the crucible and to redundant the temperature of the melt through heat transfer calculations.

Factory 2

The data obtained through the FLUKE-805 sensor was collected, whose function was to determine the number of vibrations of the machine and, using the “Fluke Connect” application, to link and collect the data on a Smartphone via Wi-Fi or Bluetooth.

Data collection was carried out on the Codim lathe for 3 days, collecting 8 readings per day, divided into 4 hours clockwise and 4 hours counterclockwise; obtaining a total of 24 measurements, when the machine was in operation without load.

Figure 2 shows the measurements indicating the direction and level of vibrations in which the signal was captured.

Analyzing the measurements; the upper limit was determined to be 2,6173 [mm/s] and the minimum limit to be 2,1507 [mm/s] in a clockwise direction. On the other hand, the maximum limit was found to be 1,6615 [mm/s] and the minimum limit to be 1,4791 [mm/s] in counterclockwise. Therefore, it is proposed to carry out preventive maintenance on the lathe, in order to reduce vibrations and additional costs caused by damage.

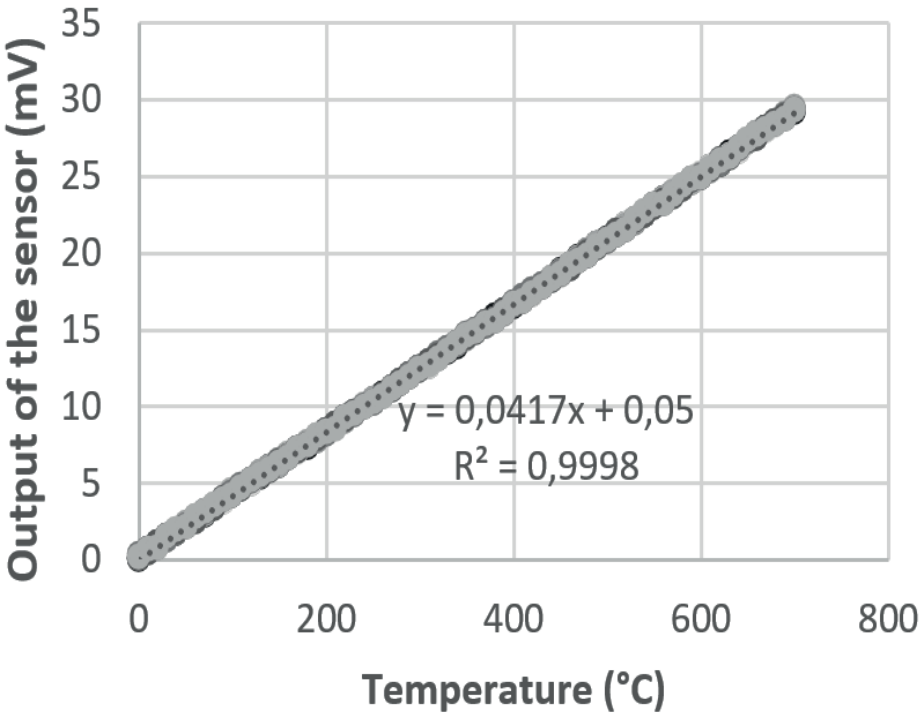

Figure 1. Temperature sensor measurement range and the temperature of the crucible of Factory 1

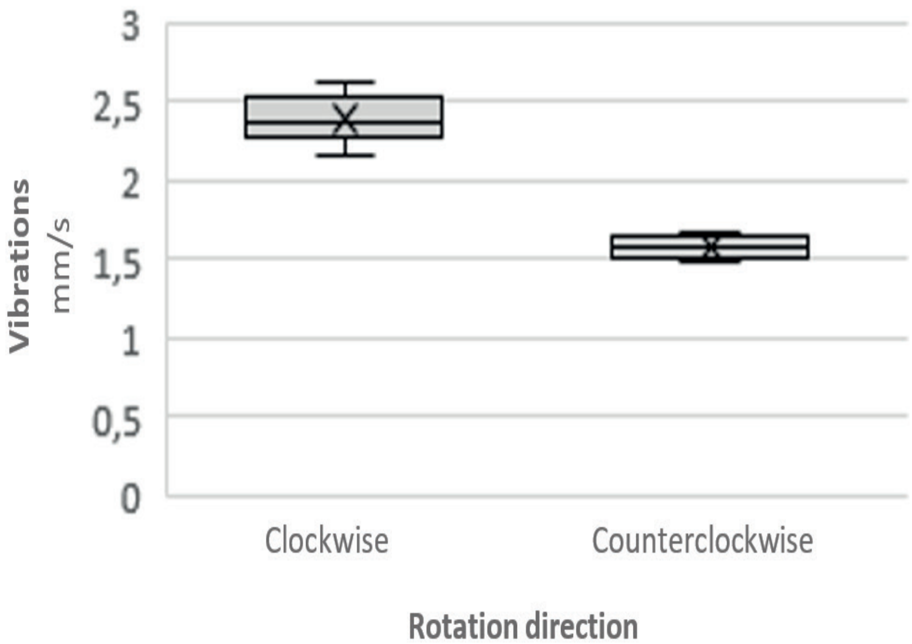

Figure 2. Vibration level measurements on the Codim Lathe of Factory 2

Factory 3

For the location of the fault recording system, the dashboard and electrical connections were redesigned. In addition, an hour meter, an LCD screen and a mobile application were implemented. In this way, when the operator indicates that a fault has occurred, the details are recorded and the information is added to the database, which will later be downloaded for pattern analysis and thus be able to establish a preventive and predictive maintenance plan in the future. Table 1 below shows the history of failures saved in the application's database with its observations or specifications.

Table 1. Failure history

Date	Revised part	Observations or specifications
May 20	Hydraulic Valve	The pedal operation did not work properly, due to the plugging of the valve.
6 months later	Blade	To increase bending capacity
1 year and 10 months later	Lower Limit Switch	The stop of the final travel of the blade does not work due to the failure of the limit switch.
1 month later	Hydraulic cylinder (hoses)	Oil leakage
1 month later	Control Board	Damage to the contactor due to working time

CONCLUSIONS

The study focused on metallurgical companies and yielded the following key findings:

Jumping to a level of Industry 4.0 is a difficult challenge for SMEs in the northern region of Ecuador; however, the proposal of Low Power solutions allows for evolution towards the implementation of Industry 4.0.

The adoption of Industry 4.0 in metallurgical companies has highlighted the importance of digital transformation as a strategic component for industrial growth. This transformation not only optimizes production but also opens new opportunities for the creation of added value and innovative services.

The implementation of Industry 4.0 technologies facilitated the adoption of predictive maintenance practices, which allowed a reduction in costs related to the replacement of parts while avoiding the need to outsource external services for similar activities.

The research presented several challenges, especially in the collection of information related to production processes, technical characteristics of equipment and existing maintenance plans. However, these obstacles were overcome as a clear methodological approach and the collaboration of the companies involved was consolidated.

The use of advanced technologies, such as real-time sensorization and data collection using intelligent systems, has led to improved operational decision-making, reducing equipment downtime and optimizing the planning of maintenance activities.

Industry 4.0 proved to have the potential to transform value chains, facilitating not only the improvement of operational efficiency but also the development of innovative products and services within the metallurgical sector in Ecuador. This transformation process, although incipient, shows a promising capacity to increase the competitiveness of local factories in the global context.

Finally, one of the main challenges identified was resistance to change at both the managerial and operational levels. However, the success of the project demonstrated that, with adequate training and demonstration of the benefits, it is possible to overcome these barriers and achieve an effective integration of new technologies.

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Data curation: Christian Vásquez.
Formal analysis: Cristian Tasiguano Pozo, Guillermo Mosquera Canchingre.
Research: Cristian Tasiguano Pozo, Guillermo Mosquera Canchingre, Luz Tobar Subía.
Methodology: Cristian Tasiguano Pozo, Luz Tobar Subía, Fernando Valencia.
Project management: Luz Tobar Subía.
Supervision: Fernando Valencia, Luz Tobar Subía.
Validation: Cristian Tasiguano Pozo, Guillermo Mosquera Canchingre.
Display: David Villarreal.
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Writing - proofreading and editing: David Villarreal, Luz Tobar Subía, Fernando Valencia, Cristian Tasiguano Pozo.