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Lean manufacturing tools applied to quality control and its impact on economic sustainability

Herramientas de manufactura esbelta en el control de calidad e impacto en la sustentabilidad económica

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ABSTRACT: This study reports a structural equation model (SEM) in which Lean Manufacturing tools associated with quality control are related to the benefits obtained in the Maquiladora industry of Ciudad Juarez (Mexico). A questionnaire was designed and applied to the regional industry to obtain information about the implementation levels of the Plan-Do-Check-Act (PDCA), Total Quality Management (TQM), and Poka-Yoke (PYK) tools and their relationship with economic sustainability (ECS). The variables were related through six hypotheses that were validated using information from 411 responses to a questionnaire. The objective of this research was to empirically and statistically measure the relationships of PDCA, PYK, and TQM with ECS to allow managers and decision-makers to better optimize the resources available to their companies. The findings indicate that the relationship between PDCA and PYK is the strongest of the models, and it is concluded that there is enough statistical evidence to state that PDCA, TQM, and PYK influence the ECS in Mexican maquiladora industries. Therefore, Top Management should focus their efforts on quality control in the use of a complete plan for the implementation of these tools to support decisions in the productive area and improve financial income.

RESUMEN: Este estudio presenta un modelo de ecuaciones estructurales (SEM) en el que las herramientas de *Lean Manufacturing* relacionadas con el control de calidad se relacionan con los beneficios obtenidos en la industria maquiladora de Ciudad Juárez (México). Se diseñó y aplicó un cuestionario a la industria regional para obtener información sobre los niveles de implementación de las herramientas Plan-Do-Check-Act (PDCA), Gestión de Calidad Total (TQM) y Poka-Yoke (PYK), y su relación con la sostenibilidad económica (ECS). Las variables se relacionaron a través de seis hipótesis que se validaron con la información de 411 respuestas a un cuestionario. El objetivo de la investigación fue medir empírica y estadísticamente las relaciones entre PDCA, PYK y TQM con la ECS para permitir a los gerentes y tomadores de decisiones optimizar mejor los recursos disponibles para sus empresas. Los resultados indican que la relación entre el PDCA y el PYK es la más fuerte del modelo, y se concluye que hay suficiente evidencia estadística para afirmar que el PDCA, la TQM y el PYK influyen en la ECS en las industrias maquiladoras mexicanas. Por lo tanto, se recomienda que la alta dirección centre sus esfuerzos en el control de calidad mediante el uso de un plan completo para la implementación de estas herramientas con el fin de respaldar las decisiones en el área productiva y mejorar los ingresos financieros.

1. Introduction

Lean Manufacturing (LM) is a business approach that focuses on delivering the best value for customers by eliminating unnecessary activities in the production process [1] and, for that, utilizes various tools to enhance final products and customer satisfaction, resulting in an efficient and effective production process [2]. LM is represented by a house that integrates tools for stabilizing and standardizing processes such as Heijunka, Kaizen, Gemba, and 5S. Its pillars include material flow, production process quality, and machine maintenance, and focus on specific production system problems.

The implementation of Lean Manufacturing tools (LMT) offers benefits in operational and productivity indicators, such as cost, quality, and delivery time. For example, by reducing waste, LM increases economic benefits and has become a sustainable business model for maximizing resource efficiency [3]. Nowadays, LM is applied in various industrial and service sectors and is recognized as an industrial production philosophy, enabling companies to achieve world-class performance [4] which must be measured from a multidimensional perspective, integrating traditional economic indicators such as profitability and return on investment with environmental and social aspects [5].

This sustainable focused approach is crucial for LMT implementation, as it ensures a company's ability to operate without exhausting its resources in a globalized environment. The relationship between LM and sustainability gained attention after the World Commission of Environment and Development's *Our Common Future* report in 1987 and the Agenda 21 Conference of the United Nations Organization in

1992, both of which emphasized the need for standardized indicators to control and monitor sustainable development at all levels [6].

The relationship between LM and sustainability has gained academic and scientific interest, and numerous studies have focused on it. Currently, 353 studies analyze this relationship, including literature reviews, trends, conceptual frameworks, and sustainability measurement in LM implementation, such as reports by, Ruben, et al. [7] and Naeemah and Wong [8]. However, the relationship between LM and sustainability remains contradictory, as evidenced by a study of 252 companies in Spain and Portugal, indicating that the relationship is inconclusive. Factors such as lack of resources, funding for green and lean projects, technology, management commitment, and communication levels may contribute to these inconclusive findings [7].

In addition, numerous studies have established a direct relationship between Lean Manufacturing (LM) and sustainability. For instance, this relationship has been validated using data from 112 companies in Saudi Arabia [9] and 176 manufacturing companies in Mexico [10]. Sustainability encompasses three dimensions: the economic, the social, and the environmental, suggesting that performance across these areas improves when LM practices are adopted. In particular, LM has been shown to enhance innovation-oriented sustainability in all three dimensions. Nonetheless, these studies have limitations in analyzing the overall impact of LM and sustainability, as specific LMT effects have not been analyzed individually.

There are also reports where specific LMTs are related to sustainability. For example, García Alcaraz, et al. [11] analyzed the effects of Total Productive Maintenance (TPM), Jidoka, and Overall Equipment Effectiveness (OEE) on environmental and social sustainability. This line of research is particularly relevant in the Mexican context, where the application of LMTs in production systems is critical. In Mexico, there are currently 5,195 manufacturing, maquiladora, and export service industries (IMMEX) at the national level, of which 488 are established in the state of Chihuahua (9.3% of the national total) and 324 in Ciudad Juarez (66.39% of the total state and 6.23% of the national total). These companies generated 2,895,151 direct jobs nationwide, including 509,949 jobs in the state of Chihuahua (17.61% of the national total) and 337,352 jobs in Ciudad Juarez (11.65% of the national total and 66.15% of the total state). These figures highlight the significant economic and social role of the Maquiladora sector, underscoring the need for further research on how specific LMTs contribute to sustainable development in this context.

The implementation level of LMT in IMMEX companies is very high, and their impact on sustainability has been analyzed from multiple perspectives. For example, Díaz-Reza, et al. [12] examined the economic benefits of three LMTs focused on material flow—5S, SMED, and Continuous Flow—through a SEM validated with 169 questionnaire responses, showing that there are relationships between TMLs and the economic benefits obtained. In a separate study, Figueroa, et al. [13] analyzed three LMTs centered on quality—TQM, Right First Time, and Wastes—and found both direct and indirect relationships with commercial benefits, including evidence of mediating effects.

However, given the number of LMTs, the relationship between them and sustainability is difficult to measure in IMMEX because they are implemented simultaneously. In particular, the Mexican manufacturing sector faces significant quality-related issues [14, 15]. Therefore, implementing the Deming Cycle is very common (PDCA, Plan, Do, Check, Act) to find solutions to quality problems measured through Total Quality Management (TQM) programs. In addition, because IMMEX makes extensive use of labor, it seeks to avoid human errors in the production system, and tools such as Poka-Yoke are widely applied to avoid quality problems in the finished product.

Although the relationships between individual Lean Manufacturing Tools (LMTs) and sustainability—such as PDCA [14, 16], TQM [17, 18], and Poka-Yoke (PYK) [10]—have been explored in previous studies, these tools have generally been analyzed in isolation. Thus, there is a need to examine how these three tools function integrated or jointly with the companies' sustainability. Therefore, to address this knowledge gap, this study aims to relate the PDCA cycle, Poka-yoke (PYK), and TQM with the economic sustainability of enterprises (ECS) using information from IMMEX to confirm empirical and statistical evidence, which will allow managers and decision-makers to better optimize the resources available to their companies, focusing on the tools that will guarantee their success and permanence in the market.

The selection of PDCA, PYK, and TQM from a wide range of LMT responds to strategic criteria aligned with research objectives in the specific context of the Mexican maquiladora industry. These tools represent the three fundamental dimensions of Lean: PDCA as a process improvement methodology that structures the quality management system; PYK, which primarily addresses material and process defects through error-proofing mechanisms; and TQM, which encompasses the human dimension by fostering a quality-oriented culture at all organizational levels. This selection allows for a simultaneous examination of the impacts on economic sustainability across multiple dimensions. Furthermore, these tools address critical issues affecting economic sustainability in the maquiladora industry, which is characterized by labor-intensive operations, high turnover rates, and significant quality challenges, as noted by García Alcaraz, et al. [19]. Finally, preliminary interviews with industry professionals identified these tools as the most widely implemented and strategically important tools for quality control and ECS.

After this brief introduction, section two presents a literature review to establish the hypotheses where the variables are defined, and the relationships between them are justified. In the third section, the methodology explains the activities conducted to achieve the research objective. The fourth section reports the results obtained from the sensitivity analysis, and the fifth section presents the conclusions and industrial implications.

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2. Literature Review and Hypothesis

2.1 Plan-Do-Check-Act (PDCA)

According to Realyvásquez-Vargas, et al. [20], the PDCA cycle is an LM tool focused on the improvement and control of product quality through continuous improvement and problem solving and consists of four phases. The first is a Plan in which improvement opportunities are identified, priorities are assigned, the current situation of the process is analyzed, and an action plan is proposed. The second stage is Do, in which the action plan is implemented, information is selected and documented, and unexpected events and lessons are learned. The third is Verify, in which the results of the action plan implementations are analyzed by comparing the performance before and after the actions. The fourth stage is the Act, which focuses on standardizing the improvements that have achieved the objective.

There have been extensive reports on the implementation of PDCA in manufacturing. For example, de Oliveira Santos, et al. [21] analyzed the environmental impacts of water consumption reduction, cost reduction, and sustainable growth. Liu, et al. [22] applied PDCA combined with SEM to manage sustainable infrastructure projects in China's industry. Milosevic, et al. [16] applied PDCA to solve problems in producing welded excavator frames when there was an increase in customer demand, seeking sustainability of the production process, and they reported a 10.67% increase in efficiency performance.

To determine the PDCA cycle implementation level in the manufacturing industry, we examine whether the quality improvement opportunities are identified and prioritized, whether the production process is monitored in real time, whether the data of the improvement projects are stored for future reference, and, above all, if the action plan is developed.

2.2 Poka-Yoke (PYK)

PYK is a quality tool within the LMT that includes the use of devices within the production area that seek autonomy to eliminate human errors and product defects [23]. One of the advantages of using PYK is that it does not require any additional steps within the process. By itself, the station design should include it and ensure that the operator uses it properly or does not remove it. There have been several reports on PYK applications in the literature. For example, Trojanowska, et al. [24] indicated that it is a support tool for operators that reduces waste, rework, and energy consumption. Krishnan, et al. [25] applied project management through Lean Six Sigma in the manufacturing industry, where (PKY) helped ensure quality benefits and reduce rework, thereby minimizing waste and energy consumption.

The PYK implementation level in the industry is measured through the good performance of error-proof devices, particularly whether they are used to prevent or control errors, support decisions to accept or reject a product, and are authorized to stop the production process upon detecting an error to initiate immediate corrective actions. In addition, the use of sounds, lights, or warning signals to indicate the occurrence of any error was also examined.

The PDCA-PYK combination as a basis for sustainability can generate results across the entire organization [26]. PYK should be included in the quality plan generated by managers to correct and avoid mistakes that operators can easily make. In other words, PDCA-PYK helps the organization minimize the risks of human error while seeking to achieve sustainability, which leads to the following hypothesis:

H_1. PDCA directly and positively affects PYK implementation in the IMMEX.

2.3 Total Quality Management (TQM)

Alharbi, et al. [27] defined TQM as a methodology that has been widely used to gain a competitive advantage in the market and as a philosophy of quality management, which focuses on improving production processes to facilitate and satisfy customer needs. At the same time, it is responsible for achieving sustainability in companies.

The application of TQM in industry has been extensively analyzed. For example, Khalfallah and Lakhal [28] analyzed TQM, JIT, and green supply chain practices to ensure environmental sustainability through SEM in US companies. Kumar, et al. [29] analyzed 14 of the main human and operational barriers to implementing TQM in the Indian industry and their relationship with sustainability, and concluded that the use of TQM has a positive and significant effect on corporate sustainability in all three dimensions. In this study, TQM implementation in the industry was assessed through the involvement of management in promoting continuous improvement in all operations, including the concept of total quality throughout the supply chain, and if decisions for improvements were justified with facts and real-time data from the production process.

The PDCA-TQM combination, as the basis of sustainability, generates improved results across the entire organization [30]. Therefore, achieving quality control is one of the objectives of the PDCA cycle of continuous improvement, as it helps to identify, prevent, and correct problems that could occur within the production process and are associated with machinery, workers, and materials, which affect the quality of the product [31]. The solution of quality problems through PDCA always helps establish new quality standards and maintain the production process without rejections and waste [32]. Therefore, we propose the following hypothesis:

H_2. PDCA directly and positively affects the implementation of TQM in the IMMEX.

The main function of PYK is to prevent errors that may compromise the product quality or affect employee safety. Therefore, the PYK-TQM combination as a basis for sustainability can generate positive results across the entire organization, avoiding defects [33]. PYK affects TQM by reducing the number of errors, production processes, waste, and resources. Therefore, these metrics favor quality standards for the production process [34]. Therefore, we propose the following hypothesis:

H_3. PYK directly and positively affects the implementation of TQM in IMMEX.

2.4 Economic sustainability (ECS)

Sudusinghe and Seuring [35] defined ECS as a part of a company's sustainability, which is divided into three pillars: economic, social, and environmental. Thus, within the economic pillar, two main groups –financial and non-financial returns– impact the ECS. The ECS has been of academic interest, and Abdul-Rashid, et al. [36] reported a study from Malaysia that measured the impact of sustainable manufacturing practices on industry sustainability through SEM and indicated that the production process has the greatest economic impact. In addition, Venugopal and Saleeshya [37] offered a sustainability framework for LM and agile tools through a house based on the hierarchical analytical process in Indian companies, where sustainability was the ceiling, supported by three pillars: economic, social, and environmental, based on technology and ethics.

To evaluate the ECS in Mexican industry, the reduction in costs due to rejected products, rework operations, recovered raw material and waste treatment, and administrative sanctions due to environmental damage or non-compliance with established norms were evaluated. The PDCA-ECS combination, as a basis for sustainability, generates results throughout the organization [21]. Identifying quality problems prevents them from generating defective products that can become waste directly or require energy consumption and man-hours to repair or recover components, thereby representing costs. In addition, they reported the economic benefits of PDCA in the mining sector, identifying problems associated with material flow interruptions that increased idle time and production costs. Therefore, we propose the following hypothesis:

H_4. PDCA directly and positively affects ECS implementation in IMMEX.

Similarly, although TQM seeks first and foremost to guarantee quality, it prevents defective products from reaching consumers, which forces companies to enforce warranties, collect products from the customer to their technical support centers, make the necessary repairs, or return a new product, paying for the return transport to the customer [38]. In addition, not having a TQM system implemented does not guarantee greater efficiency of the production system; thus, quality control would be very difficult, losing business reputation and customers that generated revenue for the company [39]. Therefore, we propose the following hypothesis:

H_5. TQM directly and positively affects ECS implementation in the IMMEX.

Human errors in the production system cost the company money and other resources; thus, preventing them through PYK generates savings and subsequent problems [40]. In other words, PYK ensures high quality by eliminating or reducing human errors and reducing the amount of rework, thus saving operator and machine time [41]. However, PYK also eliminates part checks and inspections, which saves operator time and increases productivity and, logically, the time associated with the inspection process [23]. In other words, PKY helps the organization achieve higher ECS levels, which supports the following hypothesis:

H_6. PYK directly and positively affects ECS implementation in the IMMEX.

Figure 1 illustrates the different relationships between the variables used to distinguish the established hypotheses.

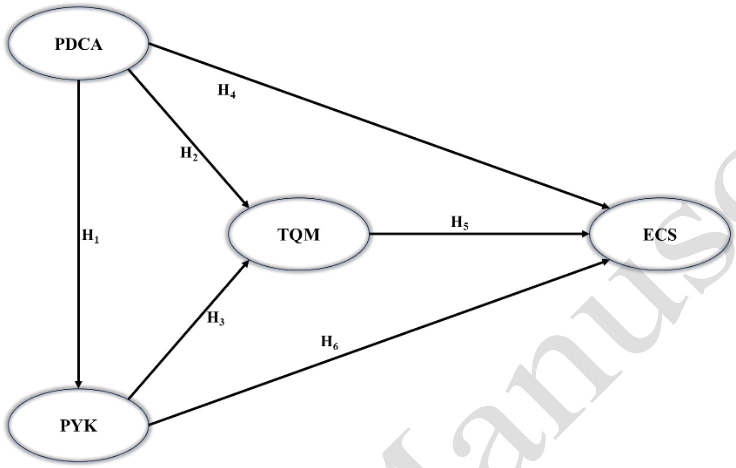

Fig 1. Proposed model

3. Methods

3.1 Development of the questionnaire

Industry information was required to validate the hypotheses proposed on **Fig. 1**. Therefore, a literature review was conducted to identify previous research related to PDCA, PYK, TQM, and ECS, proving a basis for rational validation. From this review, the items used to assess the TQM implementation level and ECS were identified, which allowed us to build a preliminary questionnaire. However, as there were no previous questionnaires applied to IMMEX, validation by judges was carried out, in which managers and active academics helped adapt the items to the regional context.

The final questionnaire consists of three sections. The first focuses on demographic aspects of the respondents, such as gender, years of experience, number of employees, and industry sector. The second section focuses on the LMTs analyzed (PDCA, PYK, and TQM), and the third section focuses on the ECS obtained from their implementation.

The final questionnaire is designed to be answered on a five-point Likert scale, where a score of one indicates that the activity is not performed or that the benefit is not obtained, while a score of five indicates that the activity is always performed or that the benefit is always obtained. The intermediate values represent ‘rarely’, ‘regularly’, and ‘almost always’ [42]. Interested readers can view the complete questionnaire as supplementary material.

3.2 Application of the questionnaire

The questionnaire was applied to the IMMEX established in Ciudad Juarez (Chihuahua, Mexico) given that we had access to it and LMTs were implemented. However, the questionnaire was administered during the sanitary contingency due to Sars-Cov2; therefore, the questionnaire was integrated into the Google Forms® platform. To prevent missing values, all questions were made mandatory in order to proceed.

An email was sent to potential respondents with an invitation to participate, explaining the purpose of the project, and a link to access the questionnaire, which remained open for responses from January 15, 2022, until August 01, 2022. If no response was obtained after two weeks, a second email was sent as a reminder. Cases with no response after the second attempt were discarded.

Respondents were required to work in the Mexican maquiladora industry and belong to a department related to production, manufacturing, or quality, ensuring familiarity with the implementation of LMTs and the benefits obtained. Additionally, participants needed to have at least one year of experience in their job positions and have completed at least two improvement projects using LMTs reported in this study (PDCA, TQM, PYK and ECS).

3.3 Information gathering and debugging

On October 5, 2022, an Excel® file was downloaded from the Google Forms® platform and then integrated into SPSS v.25® software to perform debugging operations as follows:

- Duplicate cases were identified and excluded from further analysis.
- Uncommitted respondents were identified by calculating the standard deviation of their responses; cases with a standard deviation below 0.5 were discarded [43].
- Extreme values were identified by standardizing each item. Values greater than 4 in absolute values were replaced with the median [44].

3.4 Descriptive analysis of the sample and items

SPSS v.25 software was chosen for the descriptive analysis of the information due to its ease of use and acceptance in scientific research [45, 46]. Specifically, demographic information was used to describe the sample, and cross-tabulations were reported. In addition, the median was obtained as a measure of the central tendency to describe the items: high median values indicated that the benefits of the activity were always performed, and low median values indicated the opposite. As a measure of dispersion, the interquartile range (IQR) was used, where high values in the IQR indicated a lack of consensus with the mean value of the item and low values indicated that there was consensus among the respondents.

3.5 Structural Equation Model (SEM)

3.5.1 Latent variable validation

In the model shown in **Fig. 1**, four latent variables were validated according to the following indices [47]:

- R-squared and adjusted R-squared were used to assess parametric predictive validity, with values greater than 0.2 considered accepted.
- Q-squared was used to evaluate parametric validity, with positive values similar to R-squared deemed acceptable.
- Cronbach's alpha and the Composite Reliability Index were used to measure internal validity, with values above 0.7 considered acceptable.
- The Variance Inflation Index (VIF) was used to measure collinearity between items.
- Average Variance Extracted (AVE) was used to measure convergent validity, with values greater than 0.5 considered acceptable.

It is important to mention that the estimation of indices such as Cronbach's alpha and the VIF values was performed iteratively because eliminating some items improves their reliability. Please see the supplementary material for other indices such as PLSc reliabilities (Dijkstra's rho_a's), additional reliability coefficients, discriminant validity, and T ratios.

3.5.2 Model validation

To validate the hypotheses in **Fig. 1**, the SEM methodology with the Partial Least Squares (PLS) approach integrated into the WarpPLS 8.0® software was used, which is recommended when small samples are handled, the variables do not have a normal distribution, or information is obtained in an ordinal scale [48]. Before interpreting the PLS-SEM results, the following model efficiency indices were evaluated at a confidence level of 95% [49]:

1. To measure the statistical significance of the regression parameters, the associated p-value was set to < 0.05.
2. Average R-squared (ARS) and Average adjusted R-squared (AARS) measure the model's predictive validity, where the associated p-value must be less than 0.05.
3. Average variance inflation factor (AVIF) and Average full variance inflation factor (AFVIF) measure collinearity, where values less than 5 were accepted.
4. Tenenhaus GoF measures data fit and must be greater than 0.36

3.5.3 Direct effects - validation of hypotheses

Three effects were analyzed using SEM. The direct effects between the latent variables validate the hypotheses proposed in **Fig. 1.** For each relationship between variables, a standardized parameter β was estimated as a measure of dependence, and the null hypothesis H_0: $\beta=0$ was tested against the alternative hypothesis H_1: $\beta\neq0$, with 95% confidence [49]. If, through hypothesis testing, it is concluded that $\beta\neq0$, there is sufficient statistical evidence to state that there is a relationship between the variables analyzed. In addition, the effect size (ES) was reported as a measure of variance explained by the independent variables in the dependent variable for each direct effect. The sum of all the ES for a given dependent variable corresponds to the R^2 value.

3.5.4 Sum of Indirect and Total Effects

Indirect effects between variables occur through third variables known as mediators; at least one mediator must exist for two or more segments in a relationship. This study reports the sum of indirect effects, ES of indirect effects, and the associated p-values. Finally, the total effects were reported, representing the sum of each relationship's direct and indirect effects, along with their respective ES and associated p-values.

3.5.5 Sensitivity Analysis

WarpPLS v.8.0 ® software reports the standardized indices, enabling a sensitivity analysis based on probabilities to determine occurrence scenarios for the variables in the analyzed relationships [49]. In this study, the high scenario was analyzed when the standardized variables had values greater than one ($Z \geq 1$) and low values less than one ($Z \leq -1$). We report the probability of occurrence of the following cases in the latent variables:

1. They occur in isolation or independently at high and low levels, respectively.
2. They occur simultaneously at a combination of high and low levels.
3. The conditional probability of the dependent variable was given by the occurrence of an independent variable in a combination of scenarios.

4. Results

4.1 Descriptive Analysis of the Sample

At the end of the information capture period, 411 responses were obtained from 1611 emails sent, representing a response rate of 25.51%. **Table 1** presents the respondents' industrial sectors and job positions at the time of completing the survey. It was observed that the automotive sector had the highest participation (36 %), followed by the medical and electronics sectors (18% and 14 %, respectively). In addition, engineers had the highest participation (59.12%), followed by supervisors (14.59%) and technicians (14.11%).

Table 1. Industry sector and job position

Industrial Sector	Job position				Total
	Manager	Engineer	Supervisor	Technician	
Automotive	20	90	19	19	148
Aeronautics	2	2	1	0	5
Electric	1	10	3	2	16
Electronics	7	32	10	7	56
Logistics	1	10	2	2	15

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Machining	2	5	2	4	13
Medical	5	43	10	14	72
Rubber and plastics	0	5	2	1	8
Textiles and clothing	0	3	0	0	3
Other	12	43	11	9	75
Total	50	243	60	58	411

Table 2 shows the years of experience and gender of the respondents. The results showed that 43% of the respondents were female and 57% were male. It is important to highlight that 33.8% of the respondents had between two and five years of experience in the position they held, 25.06% had between five and ten years of experience, and in third place were those with more than 10 years with 20.94%. This means that 80% of the respondents had extensive experience in their work, so it can be concluded that the information was provided by people knowledgeable about the implementation of LMTs.

Table 2. Years of experience

Gender	Years of experience at your job?				Total
	1 to 2	2 to 5	5 to 10	More than 10	
Female	38	68	42	29	177
Male	45	71	61	57	234
Total	83	139	103	86	411

4.2 Descriptive Analysis of the Items

Table 3 presents a descriptive analysis of the items used for the latent variables. In this case, the median and interquartile range of each item are presented. It was observed that all items had a median greater than 4.0, which indicates that respondents consider that benefits were almost always obtained by implementing PDCA, PYK, TQM, and ECS. However, the item with the highest median referred to the concept of quality being disseminated and promoted throughout the company, including suppliers, workers, and management staff. The item with the lowest median was related to the use of a poka-yoke to prevent errors.

Table 3. Descriptive analysis of the items

Items	Median	IQR
PDCA		
Quality improvement opportunities are identified and prioritized.	4.182	1.429
Data on the current process is described and collected.	4.171	1.433
An action plan is developed.	4.189	1.414
PYK		
Are poka-yokes used to prevent errors?	4.08	1.526
Are poka-yokes used to make a control to determine product acceptance or rejection?	4.09	1.522

When a defect is detected, are the production lines or processes stopped to make corrections immediately?	4.10	1.540
Is use made of sounds, lamps, or another warning signal to inform about the occurrence of an error?	4.14	1.554
TQM		
Participatory management aimed at continuous improvement is promoted in all operations.	4.21	1.378
The concept of total quality is promoted from the procurement of raw materials to after-sales customer service.	4.26	1.384
Decision-making for improvement is justified with facts and data.	4.20	1.417
ECS		
Reduced costs of rejects and rework	4.12	1.455
Decrease in raw material costs	4.16	1.449
Decrease in waste treatment costs	4.15	1.459
Reduction of administrative penalties for environmental mishaps	4.16	1.471

4.3 Structural Equation Model (SEM)

4.3.1 Validation of Variables

Table 4 shows the validation indices for the variables in the proposed SEM, showing that all have values within the acceptable range, indicating that the variables had sufficient parametric (R^2 and R^2 adjusted), internal (Cronbach's alpha and composite reliability), convergent (AVE), and non-parametric predictive validity (Q^2), as well as the absence of collinearity (VIF). This indicates that the variables can be integrated into the model for analysis. Please see the supplementary material for additional indices.

Table 4. The latent variables validation

Index	PDCA	TQM	PYK	ECS	Best if
R^2		0.548	0.361	0.476	>= 0.2
R^2 adjusted		0.546	0.360	0.472	>=0.2
Composite Reliability	0.954	0.945	0.928	0.952	>=0.7
Cronbach's Alpha	0.927	0.913	0.896	0.933	>=0.7
Average variance extracted	0.873	0.852	0.763	0.833	>=0.5
Full Collinearity (VIF)	2.349	2.359	1.792	1.902	<=3.3
Q^2		0.549	0.363	0.478	>=0.2

4.3.2 Model validation

The latent variables are integrated into the SEM, and the efficiency indices are listed in **Table 5**. The cut-off values for the validation indices are met, indicating that the model has predictive validity, without collinearity problems, and with a good fit of the data, especially since the GoF is 70% higher than the ideal value. The model was then interpreted based on these values.

Table 5. Model efficiency indices

Index	β, p-value	Best if
Average path coefficient (APC)	0.368, p<0.001	p<0.05
Average R^2 (ARS)	0.462, p<0.001	p<0.05
Average adjusted R^2 (AARS)	0.459, p<0.001	p<0.05
Average Block VIF (AVIF)	1.827	<=3.3
Average full collinearity VIF (AFVIF)	2.100	<=3.3
Tenenhaus GoF (GoF)	0.619	>=0.36

Figure 2 shows the SEM results. Overall, the p-value associated with all relationships was less than 0.001, indicating a 99.9% confidence level for the existence of these relationships. The R2-values for the dependent variables are also shown, indicating that ECS is explained by 48%, TQM by 55%, and PYK by 36%.

4.3.3 Validation of hypotheses - direct effects

Table 6 shows a summary of the direct effects, indicating the hypotheses established, the relationship between variables, the associated p-value for the statistical test, the effect size (ES) and the decision taken. Based on the p-values obtained, it was concluded that all relationships between the variables analyzed exist, which can be asserted with a confidence level of 99.9%. For example, for H_2, it was concluded that there was sufficient statistical evidence to state that PDCA has a direct and positive effect on TQM implementation given that when the first variable increases its standard deviation by one unit, the second variable increases by 0.568 units, which explains 40.5% of its variability.

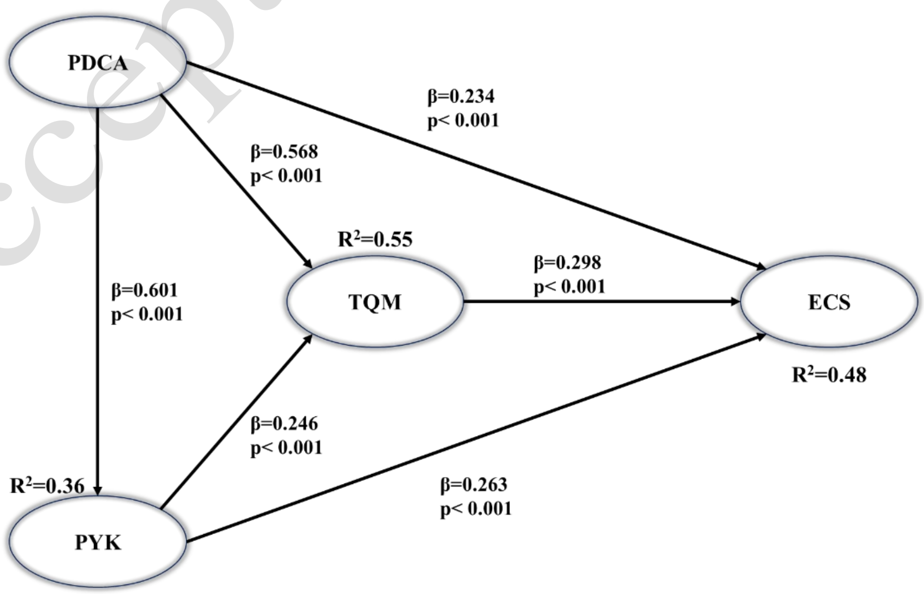

Fig 2. Evaluated model

Table 6. Summary of tested hypotheses

Hi	Relation	β (p-value)	EN	Decision
H1	PDCA→PYK	0.601 (<0.001)	0.361	Accept
H2	PDCA→TQM	0.568 (<0.001)	0.405	Accept
H3	PYK→TQM	0.246 (<0.001)	0.143	Accept
H4	PDCA→ECS	0.234 (<0.001)	0.141	Accept
H5	TQM→ECS	0.298 (<0.001)	0.184	Accept
H6	PYK→ECS	0.263 (<0.001)	0.152	Accept

4.3.4 Sum of indirect and total effects

Table 7 summarizes the sum of the indirect effects of the variables analyzed in the model, indicating the β value, associated p-value, and effect size as a measure of the variance explained by the independent variable in the dependent variable. The three relationships with indirect effects were statistically significant, and on this occasion, the PDCA→ECS relationship had the highest β value, indicating the economic importance of continuous improvement and problem-solving processes in production lines.

Table 7. Sum of indirect effects

A	From	
	PDCA	PYK
TQM	β=0.148 (p<0.001) EN=0.034	
ECS	β=0.371 (p<0.001) EN=0.047	β=0.073 (p=0.017) EN=0.035

Table 8 shows the total effects, indicating the standardized β value, associated p-value, and effect size. Again, all associated p-values were less than 0.001, indicating 99.9% confidence in the estimates. The total effects of PDCA on TQM, PYK, and ECS were the highest in the model.

Table 8. Total Effects

	PDCA	TQM	PYK
TQM	β=0.716 (p<0.001) EN=0.511		β=0.246 (p<0.001) EN=0.143
PYK	β=0.601 (p<0.001) EN=0.361		
ECS	β=0.605 (p<0.001) EN=0.364	β=0.298 (p<0.001) EN=0.184	β=0.336 (p<0.001) EN=0.194

4.4 Sensitivity Analysis

Table 9 shows the sensitivity analysis performed for each relationship in the SEM. The columns show the independent variables, and the rows refer to the dependent variables. For this analysis, scenarios where the variable had a high level were represented with a "+" sign and a "-" sign was used for scenarios with a low level. For example, the conditional probability of TQM+ occurring given that PDCA+ occurred is 0.626, indicating that implementing PDCA at a high level is 62.6% guaranteed to result in a high TQM. However, PDCA implementation levels have a 0.642 probability of generating TQM, which means that there was a high risk (64.2%) for the company's management due to the lack of PDCA implementation. A more in-depth analysis is provided in the chapter "Discussion of the results."

Table 9. Sensitivity analysis

Level		**PDCA+**	**PDCA-**	**TQM+**	**TQM-**	**PYK+**	**PYK-**
	Probs	0.241	0.163	0.248	0.134	0.204	0.190
TQM+	0.248	&=0.151 If = 0.626	&=0.007 If = 0.045				
TQM-	0.134	& = 0.002 If = 0.010	& = 0.105 If = 0.642				
PYK+	0.204	& = 0.127 If = 0.525	& =0.002 If = 0.015	& = 0.136 If = 0.549	& = 0.002 If = 0.018		
PYK-	0.190	& = 0.012 If = 0.051	& = 0.102 If = 0.627	& = 0.017 If = 0.069	& = 0.088 If = 0.655		
ECS+	0.224	& = 0.129 If = 0.535	& = 0.002 If = 0.015	& = 0.139 If = 0.559	& =0.002 If = 0.018	& = 0.122 If = 0.595	& = 0.007 If = 0.038
ECS-	0.165	& = 0.012 If =0.051	& = 0.100 If = 0.612	& = 0.012 If = 0.049	& = 0.090 If = 0.673	& = 0.007 If = 0.036	& = 0.095 If = 0.500

5. Discussion of results

5.1 From the SEM

H_1. There is sufficient statistical evidence to state that PDCA has a direct and positive effect on PYK in IMMEX. Specifically, a one-unit increase in the standard deviation of PDCA results in a 0.601-unit increase in PYK, explaining up to 36.1% of its variance. This finding indicates that, if quality problems are identified and prioritized using PDCA, PYK can be used to prevent human errors that dismiss the quality of the product. This result coincides with that of Pinto Junior and Mendes [26], who demonstrated that in a company focused on reducing water and electricity consumption, PDCA served as a useful tool for deciding when to use PYK within the improvement process.

H_2. There is sufficient statistical evidence to state that PDCA has a direct and positive effect on TQM in IMMEX, because when the first variable increases its standard deviation by one unit, the second increases by 0.568 units, explaining 40.5% of its variance. This finding indicates that collecting and processing data from the production process facilitates decision-making aimed at continuous improvement. These results are consistent with the model reported in, where TQM is achieved using the PDCA cycle, which means that quality can be ensured if the problems are planned and solved.

H_3. There is sufficient statistical evidence to state that PYK has a direct and positive effect on TQM in IMMEX, because when the first variable increases its standard deviation by one unit, the next increases by 0.246 units, explaining 14.3% of its variance. This result indicates that if defects are detected in the production process and before arriving at customers, or if it is stopped to find a solution to the problem, management promotes quality improvements in all operations by avoiding human errors. These results are in agreement with Teeravaraprug, et al. [50], who integrated PYK into the TQM implementation process, and Trojanowska, et al. [24], who indicated that PYK increased reliability. Thus, our findings confirm that IMMEX always obtains quality by reducing errors associated with human factors, given the high percentage of manual tasks in the Maquiladora industry.

H_4. There is sufficient statistical evidence to state that PDCA has a direct and positive effect on ECS in the IMMEX because when the first variable increases its standard deviation by one unit, the other increases by 0.234 units, explaining 14.1% of its variance. This result indicates that if improvements in IMMEX are driven by planning and execution focused on correcting product quality problems, the costs of rejects and rework will decrease, thereby increasing savings and financial revenue. These results agree with Milosevic, et al. [16], who indicated that TQM, TPM, and TPS allow companies to achieve economic profitability. In addition, Pinto Junior and Mendes [26] reported an annual cost reduction of 17,900 USD by applying the PDCA cycle, indicating a strong relationship between these variables.

H_5. There is sufficient statistical evidence to state that TQM has a direct and positive effect on ECS in IMMEX, because when the first variable increases its standard deviation by one unit, the following variable increases by 0.298 units, explaining 18.4% of its variance. This finding indicates that by promoting total quality concepts at all hierarchical levels in companies, a decrease in the cost of raw materials can be achieved by avoiding quality problems from the source of the process. This result agrees with Al-Tahat and Jalham [51], who indicate that TQM improves productivity and production costs, and expands the report from Aquilani, et al. [17], who indicate that TQM improves sustainability in a family owned business to industrial companies. However, quality comes from human factors, and maquiladora must have several operator skills to guarantee TQM benefits [52].

H_6. There is sufficient statistical evidence to state that PYK has a direct and positive effect on ECS in IMMEX, because when the first variable increases its standard deviation by one unit, the second increases by 0.263 units, explaining 15.2% of its variance. This means that error-proofing devices are useful in preventing errors and determining whether the product is accepted or rejected, which directly and positively impacts the reduction of rejects and rework costs, and increases savings and financial income. These results are consistent with those of García-Alcaraz, et al. [53], who reported a reduction in defective products and resource consumption, such as materials, energy, inventory, and even products discarded into the environment. Moreover, error prevention also impacts healthcare sector applications, thus avoiding legal claims [54]. Therefore, the implementation of PYK for IMMEX is necessary to achieve ECS.

5.2 Sensitivity analysis

In this research, it is assumed that PDCA is the tool that serves as the basis for quality programs and is supported by PYK and TQM to achieve ECS, so the probabilities of occurrence at low and high levels are analyzed and discussed, which are based on the information in **Table 9**.

PDCA+ directly favors the occurrence of TQM+, PYK+, and ECS+, with probabilities of 0.626, 0.525, and 0.535, respectively, indicating the importance of identifying and solving problems in production lines to guarantee quality and financial income. In contrast, when PDCA- occurs, the probabilities of obtaining TQM-, PYK-, and ECS- are 0.642, 0.627, and 0.612, respectively, representing a risk for managers in IMMEX, which is why managers are urged to focus their efforts on planning for quality control that will allow them to identify the problems that have negative economic effects.

TQM+ directly favors the occurrence of PYK+ and ECS+ with probabilities of 0.549 and 0.559, respectively, which confirms the importance of quality in IMMEX; that is, TQM guarantees economic returns. Moreover, if TQM+ occurs, the probability of obtaining PYK- and ECS- is low; therefore, investment in TQM will always bring economic benefits. However, in the case of TQM-, it favors the occurrence of PYK- and ECS- with a probability of 0.655 and 0.673, respectively, indicating a high risk to ECS when TQM is given less importance within quality programs.

Finally, PYK+ favors the occurrence of ECS+ with a probability of 0.595, which indicates that PYK is of utmost importance within quality control, having devices within the productive area that avoid creating errors, waste, or rework in which the ECS is directly benefited. In addition, the existence of PYK- favors the occurrence of ECS- in 0.500; therefore, the risk of affecting the ECS of the companies within the IMMEX is great and is something that top management must avoid.

6. Conclusions and Industrial Implications

6.1 Conclusions

Based on the research findings, the relationship between lean manufacturing tools focused on quality control and economic sustainability reveals several critical insights that extend beyond the statistical validation of the hypotheses.

The PDCA cycle has emerged as the cornerstone of effective quality improvement systems in the Maquiladora industry. Its strong influence on TQM implementation (β=0.568) and error-proofing systems (β=0.601) demonstrates that systematic problem-solving approaches create a foundation for comprehensive quality cultures. Without this structured approach to improvement, quality initiatives risk becoming isolated interventions, rather than integrated systems.

This study revealed an interconnected quality ecosystem rather than isolated tools. The synergistic relationships between PDCA, PYK, and TQM suggest that maquiladoras should not be viewed as independent methodologies, but as complementary elements of a holistic quality strategy. This integrated approach yields economic benefits that exceed those of piecemeal implementation, as evidenced by the 48% explanation of the economic sustainability variance through the combined model.

These findings challenge the common industrial practice of implementing error-proofing devices without systematic quality management systems. The data suggests that Poka-Yoke implementation yields significantly higher economic returns when embedded within comprehensive TQM frameworks and guided by the PDCA methodology, indicating that contextual implementation is more valuable than the tools themselves.

Perhaps most significantly, the sensitivity analysis reveals an asymmetrical risk profile of quality systems, and the negative economic impact of neglecting quality tools (64.2% probability of low economic sustainability when PDCA is neglected) exceeds the positive impact of their implementation (53.5% probability of high economic sustainability when PDCA is implemented). This asymmetry suggests that quality systems serve as much as insurance against economic losses as they do as drivers of improvement.

6.2 Industrial Implication

This study provides a clear direction for strategic quality investments in maquiladora leadership. The priority should be to establish robust PDCA methodologies as the foundation of quality initiatives before making significant investments in specific error-proofing technologies or broader TQM programs. This approach optimizes resource allocation and increases the likelihood of economic return.

The 36.1% variance in PYK implementation explained by PDCA suggests that approximately one-third of error-proofing effectiveness is determined by the quality of the problem-solving approaches. Therefore, manufacturing executives should ensure that error-proofing device implementations are preceded by thorough problem analysis and are solution-focused, rather than driven solely by compliance-oriented requirements.

Organizations should develop integrated performance metrics that reflect the interconnected nature of these quality systems. Companies should create composite indicators that reflect their systemic interaction and collective impact on economic outcomes, rather than measuring PDCA projects, TQM implementation, and error-proofing effectiveness in isolation.

The probability data from the sensitivity analysis provides a compelling business case for quality investments, particularly in industries with thin profit margins, such as maquiladoras. Quality system implementation should be framed not merely as a strategy for continuous improvement but also as a form of financial risk mitigation, with a 64.2% risk of poor economic performance without PDCA systems serving as a powerful motivator for investment.

The findings support a capability maturity model approach to quality implementation, in which organizations progressively build from foundational PDCA methodologies toward more sophisticated TQM cultures. This staged implementation allows for capability building and increases the likelihood of sustained economic benefits compared with the simultaneous implementation of multiple quality initiatives.

For the broader maquiladora industry in Mexico, these findings highlight the need for sector-wide capability development using systematic problem-solving methodologies as a foundation for international competitiveness. Industry associations and economic development agencies should prioritize PDCA training as the cornerstone of workforce development programs to strengthen the economic sustainability of this critical manufacturing sector.

7. Limitations and future research

This study was conducted during the COVID-19 pandemic, and because of this, people were restricted from accessing companies. Therefore, the number of potential respondents was reduced by conducting online surveys. Similarly, many LMTs are implemented in IMMEX, and this study only reports three LMTs that are only related to the ECS. Therefore, future work is as follows:

- Continue surveys and evaluations until 2023 to increase the sample size and analyze LM implementations with social sustainability, as the pandemic has severely affected employee motivational status.
- The survey was applied to other cities and Mexican states where IMMEX exists to carry out comparative analyses from cultural and social points of view as well as the characteristics of the geographical environment. Analyze the impact of these LMTs and others on social and environmental sustainability, allowing us to see how continuous improvement can be directed toward workers and the environment.

8. Declaration of competing interest

We declare that we have no significant competing interests, including financial, non-financial, professional, or personal interests, interfering with the full and objective presentation of the work described in this manuscript.

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11. Author contributions

L. J. Márquez-Figueroa and J. L. García-Alcaraz: Conceptualization. J. L. García-Alcaraz and J. R. Díaz-Reza: Methodology. A. Realyvásquez-Vargas: Software. R. Puig-Vidal and A. Realyvásquez-Vargas: Validation. L. J. Márquez-Figueroa: Formal Analysis. J. L. García-Alcaraz and L. J. Márquez-Figueroa: Research. J. L. García-Alcaraz: Resources. A. Realyvásquez-Vargas and R. Puig-Vidal: Data curation. J. R. Díaz-Reza and A. Realyvásquez-Vargas: Visualization. J. L. García-Alcaraz: Supervision. L. J. Márquez-Figueroa and J. L. García-Alcaraz: Project management. L. J. Márquez-Figueroa and J. R. Díaz-Reza: Funding acquisition, All authors have read and agreed to the published version of the manuscript.

11. Data availability statement

There is a folder at the following repository at https://doi.org/10.17632/3n2twpcmdr.1, containing 2 files as follows: 1) Project created in WarpPLS v8.0 with the data of the model. 2) An MS Excel file with seven sheets containing full outputs, correlations among latent variables, T-ratios, Djisktra ratios, reliability indices, and HTMT ratios for discriminant validity and model fit indices for a) Firsts order model; b) second-order model; and c) mediated model.

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