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MODELADO DE PROCESOS DE PRODUCCIÓN CON ECUACIONES ESTRUCTURALES: CASOS DE ESTUDIO EN LA INDUSTRIA MAQUILADORA (MÉXICO)

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Dedicatoria

Quizá el escribir una tesis no sea tan complicado como escribir una dedicatoria, ya que se tienen muchos sentimientos y me es muy difícil expresarlos con palabras. Esos sentimientos son gracias a las personas más importantes en mi vida, mi familia y mis amigos, es por eso que quiero dedicar este trabajo a ellos:

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Resumen

En este trabajo se utiliza la técnica del modelado de ecuaciones estructurales para medir el efecto que tienen ciertos factores críticos (FCE) sobre los beneficios obtenidos de la implementación de dos herramientas de manufactura esbelta, en este caso, *Single Minute Exchange of Dies* (SMED) y Mantenimiento Preventivo Total (TPM). Esto se llevó a cabo mediante la elaboración de dos cuestionarios que se desarrollaron en base a la revisión de literatura en diferentes bases de datos. Dichos modelos se ejecutaron en el software WarpPls 5.0®.

El primer cuestionario relaciona los FCE en la implementación de la metodología SMED con los beneficios obtenidos dentro de la industria de la maquiladora en Ciudad Juárez, México. Este cuestionario cuenta con 19 ítems divididos en cuatro variables latentes, asimismo se identificaron un total de 25 beneficios que se obtienen a raíz de la implementación de la herramienta. El segundo cuestionario relaciona los FCE en la implementación de la metodología TPM y los beneficios obtenidos dentro de la industria maquiladora en Ciudad Juárez. Este cuestionario cuenta con un total 82 ítems divididos en nueve variables latentes, de la misma forma, se identificaron un total de 22 beneficios, los cuales se dividieron en beneficios de productividad, beneficios de seguridad y beneficios para la organización.

Los sectores de interés a estudiar, como ya se mencionó, fueron la industria maquiladora en Ciudad Juárez, México donde se recabo la información por medio de estos cuestionarios. De la información reunida se desprenden 3 artículos relacionados con los FCE en la implementación de SMED TPM.

En el caso de SMED, el primer artículo se realiza mediante encuesta aplicada a 250 personas que trabajan dentro de las empresas maquiladoras en Ciudad Juárez. Esta encuesta incluye las 4 etapas que contienen 14 actividades o ítems en la implementación de la metodología SMED. Los resultados del modelo revelaron que la Etapa 1 de la implementación de SMED, conocida como la Etapa de Identificación, tiene efectos directos e indirectos en todas las otras etapas de SMED, siendo la etapa más importante.

El segundo artículo reporta resultados de la encuesta aplicada a 373 personas que trabajan dentro de las empresas maquiladoras en Ciudad Juárez. Esta encuesta engloba las 4 etapas de SMED (15 ítems o actividades) con los beneficios (25 ítems) obtenidos después de la implementación de la metodología. Se encontró que las empresas manufactureras en Ciudad Juárez deben comenzar con la etapa de planificación para identificar actividades de producción interna importantes y convertirlas en actividades externas. De hecho, la etapa de planificación de SMED tiene efectos directos e indirectos en etapas posteriores y beneficios de SMED.

El tercer artículo relaciona cuatro variables latentes mediante un modelo de ecuaciones estructurales. Las cuatro variables involucradas en este modelo son el Compromiso Gerencial, Implementación de Mantenimiento Preventivo, Implementación de TPM y

Beneficios de Productividad. La información se obtuvo mediante la aplicación del cuestionario dentro de la industria maquiladora en Ciudad Juárez, México. Se obtuvieron un total de 368 cuestionarios válidos. Los resultados muestran que el compromiso gerencial es crítico para lograr beneficios de productividad, mientras que el mantenimiento preventivo es indispensable para el TPM. Estos resultados pueden alentar a los gerentes de las compañías a enfocarse en el compromiso gerencial e implementar programas de mantenimiento preventivo para garantizar el éxito del mantenimiento productivo total.

Abstract

In this paper, the structural equation modeling technique is applied to measure the effect that certain Critical Success Factors (CSF) have on the benefits obtained from the implementation of two lean manufacturing tools, in this case, the *Single Minute Exchange of Dies* (SMED) and the Total Preventative Maintenance (TPM). In addition, it was carried out through the elaboration of three questionnaires that were developed based on the literature review in different databases; these models were executed in the WarpPls 5.0® software.

Moreover, the first questionnaire relates the CSF in the SMED implementation methodology with the benefits obtained within the maquiladora industry in Ciudad Juárez, Mexico. In addition, this questionnaire has 19 items divided into four latent variables, and a total of 25 benefits obtained from the implemented tool were identified. Also, the second questionnaire links the CSF in the TPM implementation methodology with the benefits obtained within the maquiladora industry in Ciudad Juárez; this questionnaire has a total of 82 items divided into nine latent variables, in the same way, a total of 22 benefits were identified that were divided into productivity benefits, safety benefits, and benefits for the organization.

The sector of interest to study, as it was already mentioned, were the maquiladora industry in Ciudad Juárez, Mexico, where the data was collected through these questionnaires in this sector. In addition, according to the gathered data, 3 articles are released; two are related to the CSF in the SMED and TPM.

In the case of SMED, the first article is done through a survey applied to 250 people who work within the maquiladora companies in Ciudad Juárez; this survey includes the 4 stages that integrate 14 activities or items in the SMED methodology implementation. Also, the results from the model shown that the Stage 1 from the SMED implementation, known as Identification Stage, has direct and indirect effects in all the other SMED stages, being the most relevant stage.

Furthermore, the second article reports results from the survey applied to 373 people who work within the maquiladora companies in Ciudad Juárez; this survey covers the 4 stages of SMED (15 items or activities) with the benefits (25 items) obtained after the methodology implementation. In addition, it was found that the manufacturing companies in Ciudad Juárez must begin with the planning stage to identify significant internal production activities in order to turn them into external activities. In fact, the planning stage of SMED has direct and indirect effects in later stages and benefits.

As a matter of fact, the third article describes four latent variables through a structural equation model. In addition, the four variables involved in this model are the Management Commitment, Preventive Maintenance Implementation, TPM Implementation, and Productivity Benefits. Also, the data was obtained by applying the questionnaire within the maquiladora industry in Ciudad Juárez, Mexico; a total of 368 valid questionnaires were obtained. Additionally, the results show that the management commitment is critical

to achieve productivity benefits, while preventive maintenance is essential for the TPM implementation. These results may encourage company managers to focus on management commitment and implement preventive maintenance programs to ensure the success of total productive maintenance.

1. Introducción

Una cadena de suministro (CS) comprende distintas actividades, desde la materia prima hasta el usuario final, una parte muy importante dentro de la CS es la transformación de esas materias primas en productos terminado, el cual será consumido por el usuario final. Dentro de este proceso de transformación de materias primas se encuentran las maquiladoras las cuales son empresas que importan materiales sin pagar aranceles; su producto se comercializa en el país de origen de la materia prima.

Estas empresas se encuentran constantemente en búsqueda de la reducción de los desperdicios que se generan en los distintos procesos producción, en ese sentido, se hace uso de distintas herramientas de *Lean Manufacturing* (LM) cuyo objetivo es la reducción de estos desperdicios, y de esa forma obtener ciertos beneficios. Para la implementación de las herramientas LM se desarrollan ciertas actividades, las cuales se pueden clasificar bajo una categoría y se pueden formar variables que se pueden relacionar entre si y poder encontrar ciertas dependencias entre ellas, y a su vez poder generar predicciones del comportamiento que tendrán. De esta manera se facilita el proceso de la toma de decisiones.

En la CS de productos perecederos también existen distintas actividades para la producción de productos, estas actividades incluyen el proceso y la calidad del producto desde la granja hasta la entrega de los productos perecederos. De la misma forma, en esta CS también se ciertas actividades en las diferentes etapas, que pueden formar variables y relacionarse entre sí para encontrar ciertas dependencias entre ellas.

Para el análisis de este fenómeno, existe la técnica del modelado de ecuaciones estructurales, en el cual se analiza la relación entre estas variables.

En este trabajo se presentan una serie de modelos de ecuaciones estructurales que son usados en la industria maquiladora de Ciudad Juárez (México):

1.1 El sector de la industria maquiladora de Ciudad Juárez (México)

Durante más de medio siglo, la economía de México ha dependido en gran medida de las maquiladoras como una fuente prolífica de creación de empleo e ingresos por exportaciones (Munguia et al., 2018). Las maquiladoras son compañías de propiedad extranjera establecidas en México, y generalmente importan materias primas y productos de exportación al país y otras, como los Estados Unidos y Canadá, utilizando los beneficios fiscales del Tratado de Libre Comercio de América del Norte (INEGI, 2018).

Las plantas maquiladoras en México generalmente son empresas de propiedad extranjera, muchas de las cuales son subsidiarias de empresas multinacionales con sede en EE. UU., que exportan principalmente al mercado de los EE. UU. bajo aranceles preferenciales o libres de aranceles sobre sus insumos intermedios importados (Hernandez, 2004). Además, la difusión de las maquiladoras surgió de la inclusión de México en el Tratado de Libre Comercio de América del Norte (TLCAN) con los EE. UU. y Canadá, ya que pueden exportar sus productos a estos países (Hernandez, 2004). En la mayoría de los casos, la operación de maquiladoras consiste en procesos de montaje intensivos que requieren mucho trabajo manual (Avelar-Sosa, García-Alcaraz, Vergara-Villegas, Maldonado-Macías, & Alor-Hernández, 2015).

Estas compañías siempre están listas para atender órdenes de producción de empresas matrices ubicadas en el exterior (INEGI, 2018). Sin embargo, dado que tales órdenes de producción generalmente varían en cantidad y diseño del producto, el cambio ocurre con frecuencia. Por esta razón, SMED se ha convertido en una técnica tradicional utilizada en el sector maquilador.

Afortunadamente, parece que las empresas manufactureras mexicanas están familiarizadas con las actividades y beneficios de implementación de SMED. Sin embargo, debido a que los cambios en las maquinarias ocurren con tanta frecuencia, el efecto de SMED generalmente se desconoce y, por lo tanto, raramente se analiza al informar los beneficios de la compañía.

Mucho ha cambiado desde entonces y las maquiladoras han evolucionado enormemente para especializarse en áreas clave de la producción industrial, incluida la fabricación de piezas para las industrias aeroespacial, médica y automotriz, entre otros nichos (Sargent & Matthews, 2003).

A partir de la firma TLCAN, la manufactura y por ende las empresas maquiladoras de exportación son una fuente generadora de divisas para el país, asimismo, la consolidación de este tipo de actividades en el mundo, ofrece a los países en desarrollo una buena opción para que, a través de las operaciones de subcontratación internacional, sus productos compitan en los mercados externos (IMMEX, 2018).

La actividad maquiladora de exportación en México ha adquirido mucha importancia, ya que ha permitido tener un desarrollo tecnológico, una participación creciente en los mercados internacionales y una capacitación constante para los trabajadores que se emplean en este tipo de industrias (IMMEX, 2018).

De acuerdo con cifras del INEGI (2018), a marzo del 2018 se contaba con 5518 industrias maquiladoras, manufactureras y de servicios de exportación (IMMEX) en el país, de las cuales, el estado de Chihuahua cuenta con 510, estas equivalen a un 9.25% del total a nivel nacional. Asimismo, de esas 510, Ciudad Juárez cuenta con 332, lo cual equivale a un 65.10% a nivel estado.

De la misma manera, el total de empleados contratados en el estado asciende a 371,294, de los cuales 268,761 son los contratados por industrias IMMEX establecidas en Ciudad Juárez, lo cual equivale a un 72.38% de la fuerza laboral.

Cabe mencionar que, de los 371,294 trabajadores, 329,578 son contratados directamente por las empresas en el estado. En Ciudad Juárez se cuenta únicamente con 244,501 contratados directamente por las empresas. Para el mismo periodo, el país registró un ingreso de 166,793,454 (miles de pesos mexicanos), de los cuales, Chihuahua tuvo ingresos por 2,603,700 (miles de pesos mexicanos), por último, Juárez generó ingresos por 339,098 (miles de pesos mexicanos).

De la misma manera, de acuerdo a AMAC (2018), en 2017 la inversión extranjera directa en el estado de Chihuahua fue del 58% para el sector de Manufactura, seguido de del sector de transporte con un 25%, los servicios financieros con un 7%, la minería con 6%, comercio con 2% y el resto fue invertido en otros sectores.

Asimismo, del 100% de la situación geoeconómica en Ciudad Juárez, el 66% proviene del sector industrial, el 31 del sector comercio y el 3% de la construcción. El sector industrial de Ciudad Juárez se distribuye en varios giros, los cuales se pueden apreciar en la Tabla 1, en donde se puede observar que el sector que predomina es el automotriz, seguido del sector electrónico.

Tabla 1. Sectores industriales en Ciudad Juárez

Sector Industrial	Participación
Automotriz	32%
Electrónicos	29%
Plásticos / Metal	12%
Empaque	8%
Call center	8%
Médico	7%
Otros	4%

Asimismo, en la Tabla 2 se puede observar la distribución de empleo por sector, se puede ver que el sector que más emplea personas es el automotriz con un 38%, seguido del sector electrónico/eléctrico.

Tabla 2. Porcentaje de empleo de acuerdo al sector Industrial

Sector Industrial	Porcentaje de empleo
Automotriz	38
Electrónicos / Eléctricos	37
Plásticos / Metal	3
Empaque	3
Call center	4
Médico	9
Otros (etiquetas)	6

1.2 Lean Manufacturing en el sector industrial

Una forma de entender el proceso de la evolución industrial y la naturaleza heterogénea de las maquiladoras es observar detenidamente la difusión de las mejores prácticas, el inicio de las mejores prácticas en las plantas maquiladoras a principios de la década de 1980 está asociado con la introducción del Sistema de Producción Japonés (JPS), más comúnmente conocido en México como producción "flexible" o *"Lean"*, aunque la ganancia o pérdida de competitividad se basa, en primer lugar, en el desempeño y progreso de una empresa hacia el JPS, los factores externos también hacen una gran diferencia (Carrillo & Zárate, 2009). En este sentido, las mejores prácticas pueden entenderse desde la perspectiva de la mejora industrial (Carrillo & Zárate, 2009).

Lean manufacturing se basa en la lógica de eliminar actividades que no agregan valor a los sistemas de producción, especialmente los asociados con el tiempo transcurrido, los métodos, los procesos, los lugares, las personas y los movimientos (Garre, Nikhil Bharadwaj, Shiva Shashank, Harish, & Sai Dheeraj, 2017). Entonces, para una organización *lean*, el objetivo final es proporcionar un valor perfecto para el cliente a través de un proceso de creación de valor perfecto que no genera desperdicios (Garre et al., 2017).

Lean es "un conjunto de principios, filosofías y procesos de negocio que permiten su implementación" (Rose, Deros, Rahman, & Nordin, 2011), asimismo, Wilson (2010) lo define como un conjunto completo de técnicas que, cuando se combinan y maduran, permitirán reducir y luego eliminar los siete desperdicios, este sistema no solo hará que su empresa sea más *lean*, sino que posteriormente será más flexible y más receptiva al reducir los desperdicios.

La implementación de *Lean Manufacturing* se ha convertido en una necesidad entre las organizaciones que desean operar en un mercado global, aunque sus beneficios de implementación son innegables, no muchas empresas han recurrido a la implementación de sus principios y filosofías (Anand & Kodali, 2009).

Aunque el término "*lean*" es ampliamente conocido hoy en día, la implementación de *Lean* aún plantea una serie de desafíos, la exitosa transformación *Lean*, como se describe en el proceso de una empresa que pasa de una vieja forma de pensar al pensamiento *lean* por parte de expertos y profesionales en *lean*, se basa en una gran cantidad de factores (Alefari, Salonitis, & Xu, 2017). La identificación y clasificación de estos factores críticos de éxito han sido el foco de una gran cantidad de estudios (Alefari et al., 2017). Algunos de estos factores críticos de éxito incluyen la comunicación, el cambio cultural y el compromiso de la alta dirección (Alhuraish, Robledo, & Kobi, 2017).

Hoy en día, las empresas están impulsadas por una demanda del mercado caracterizada por una competencia feroz, un ritmo de negocios acelerado, por un lado, la fabricación experimenta ciclos de producción reducidos y tamaños de lotes reducidos; por otro lado, la variedad de tipos de productos y su personalización están aumentando, así como las demandas de los clientes cambian rápidamente (D'Antonio, Bedolla, & Chiabert, 2017). Por lo tanto, para mantener y mejorar su ventaja competitiva, las organizaciones líderes en diferentes sectores industriales necesitan mejorar la optimización y eficiencia de los procesos (D'Antonio et al., 2017).

El objetivo principal de la producción lean es reducir los costos y aumentar la productividad al eliminar los desperdicios (Botti, Mora, & Regattieri, 2017), estos desperdicios afectan negativamente la productividad de las empresas de fabricación: reparación, sobreproducción, movimiento, movimiento de materiales, esperas, inventario y procesamiento (Botti et al., 2017), mano de obra, equipo o espacio de piso (Das, Venkatadri, & Pandey, 2014).

Varias industrias y procesos de fabricación, desde la industria automotriz hasta la industria de servicios, integran sus estrategias de producción con principios de pensamiento esbelto, con el objetivo de mejorar la productividad y la calidad mediante la reducción de costos (Botti et al., 2017).

Para satisfacer las expectativas del cliente, se establecen estándares de calidad que posteriormente aumentan las ventas, por lo tanto, las empresas deben estar dispuestas a adaptarse a los diferentes estándares de calidad para tener éxito en otros mercados (Hadjimarcou, Brouthers, McNicol, & Michie, 2013). De esta manera, la calidad se ve como uno de los contribuyentes más importantes que conducen al crecimiento de las empresas en los mercados internacionales (Feigenbaum, 1982).

Una fábrica *Lean* es capaz de producir productos solo en la suma de su tiempo de contenido de trabajo de valor agregado, las características de un modelo *lean* típico incluyen: producción de una unidad a la vez; tiempo sin valor agregado eliminado; producción en el tiempo de contenido de trabajo solamente; reubicación de los recursos requeridos hasta el punto de uso; y todos los procesos se equilibran para producir a la misma tasa del *Takt* (Pattanaik & Sharma, 2009).

Algunas de las técnicas más importantes de LM incluyen gestión de calidad total (TQM), mantenimiento productivo total (TPM), 5S, *single minute Exchange of dies* (SMED), kanban, kaizen, pokayoke, Jidoka, entre otros (Vinodh & Balaji, 2011), en la Figura 1 se muestra la casa de LM, en donde en los cimientos se tienen herramientas de diagnóstico, operativas y de seguimiento. En este trabajo se reportarán dos herramientas operativas, en este caso, SMED y TPM.

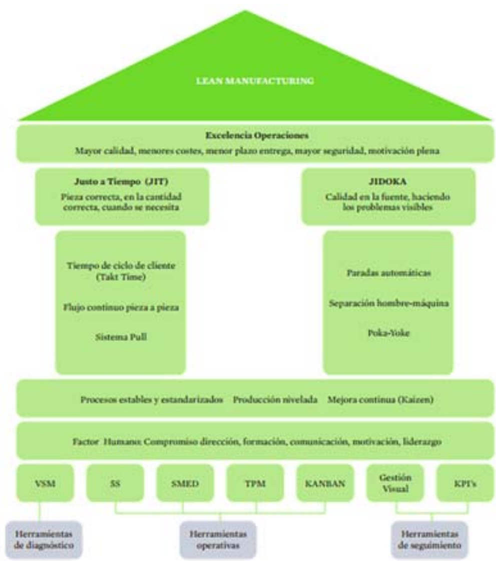

Figura. 1. Casa de LM. Fuente (Gonzalez Rivas, 2016)

La clave del éxito en muchas empresas de manufactura es crear un entorno de fabricación más ágil, flexible y receptivo (Jasti & Kodali, 2015) y la capacidad de las empresas para realizar un cambio rápido de un producto a otro es un paso clave hacia este logro (Braglia, Frosolini, & Gallo, 2016). SMED es una práctica clave de LM, ya que se enfoca directamente en la flexibilidad, la cual es la capacidad de cambiar rápidamente de una actividad conocida a la siguiente (Kim, 2015). SMED siempre busca mejorar la flexibilidad hasta que llegue a cierto flujo de una sola pieza en la secuencia correcta para responder a la demanda instantánea de los clientes (Kim, 2015).

De esta manera, las empresas se ven obligadas a producir lotes más pequeños, sin embargo, producir tamaños de lote más pequeños causa más cambios. (Boran & Ekincioğlu, 2017), ya que un desperdicio significativo es el de la sobreproducción, el cual se debe principalmente a las actividades de cambio de modelo: los largos cambios hacen que sea casi imposible ejecutar lotes pequeños de piezas, sincronizados con la demanda del cliente (Braglia et al., 2016).

Tanto la configuración como el cambio de modelo se han definido como el proceso de cambio de modelo de un producto o número de parte a otro en una máquina al cambiar piezas, dados, moldes o accesorios (Srikamaladevi Marathamuthu, Jebaraj Benjamin, & Murugaiah, 2013). El concepto establece que cualquier cambio de máquina siempre debe tomar una cantidad de tiempo específica, y las tareas deben estandarizarse para ese cambio, por lo tanto, cuando hay un cambio planificado en la máquina, se cuantifica el tiempo que llevará y los recursos que requerirá (Lozano, Saenz-Díez, Martínez, Jiménez, & Blanco, 2017). SMED está comprendida dentro de la filosofía de producción de LM y sus objetivos son reducir el desperdicio en el sistema de producción y estandarizar los tiempos de cambio de modelo (Lozano et al., 2017).

Como se ha mencionado anteriormente, LM ha sido ampliamente implementada por las organizaciones de fabricación para lograr la excelencia operativa, y de esta manera cumplir con los objetivos de la organización tradicional y contemporánea, como la rentabilidad, la eficiencia, la capacidad de respuesta, la calidad y la satisfacción del cliente (Garza-Reyes, 2015). Otro de los elementos que permiten obtener los beneficios mencionados es TPM (Garza-Reyes, 2015), la cual es relevante para maximizar la efectividad del equipo, mejorar su eficiencia general, ayudar a las organizaciones a obtener beneficios con este enfoque basado en un modelo integral de sistema de mantenimiento productivo que ayuda a la vida del equipo, de esta manera mantenerlo en buenas condiciones para respaldar su negocio (Mwanza & Mbohwa, 2015), ya que las malas condiciones de los equipos conducen a la pérdida de ventajas competitivas.

Una práctica de mantenimiento inadecuada causa una reducción en el rendimiento y la confiabilidad de la fabricación (Lai Wan & Tat Yuen, 2017). TPM cubre la prevención de mantenimiento, el mantenimiento preventivo y el mantenimiento relacionado con mejoras, con el objetivo final de prevenir pérdidas y desperdicios, TPM es aceptado globalmente por las organizaciones de manufactura como estrategia de mantenimiento más efectiva para mejorar el rendimiento de mantenimiento (Lai Wan & Tat Yuen, 2017).

La investigación ha demostrado que TPM tiene un impacto directo en la mejora del rendimiento general del equipo de producción (Lai Wan & Tat Yuen, 2017).

1.3 Problema de Investigación

Las maquiladoras se caracterizan por su alta capacidad tecnológica y habilidades y habilidades específicas y como ya se ha mencionado en secciones anteriores, el en 2017 la inversión extranjera directa en la industria maquiladora en Ciudad Juárez fue de 66% del total en el estado, es por eso que esta industria es de las más importante en cuanto a inversión. Estas compañías siempre están listas para atender órdenes de producción de empresas matrices ubicadas en el exterior. Sin embargo, dado que tales órdenes de producción generalmente varían en cantidad y diseño del producto, el cambio ocurre con frecuencia.

Por esta razón, SMED se ha convertido en una técnica tradicional utilizada en el sector maquilador. Afortunadamente, parece que las empresas manufactureras mexicanas están familiarizadas con las actividades y beneficios de implementación de SMED. Sin embargo, debido a que los cambios en las maquinarias ocurren con tanta frecuencia, el efecto de SMED generalmente se desconoce y, por lo tanto, raramente se analiza al informar los beneficios de la compañía.

Dentro de la literatura se han identificado muchas investigaciones sobre la implementación de SMED, por ejemplo, en la industria farmacéutica (Karam, Liviu, Cristina, & Radu, 2018), donde se reporta una disminución del tiempo de cambio de modelo en un 30%, asimismo se presentan algunos beneficios económicos. De la misma forma, en la industria automotriz (Rosa, Silva, Ferreira, & Campilho, 2017) se implementó SMED y se obtuvo una reducción del 58.3% en el tiempo de cambio del modelo, se aplicó la SMED en una celda de manufactura y se redujeron los tiempos de cambio de modelo, al hacer esto, se logró un aumento en el la eficiencia general del equipo del 77 al 85%, además, la productividad aumentó de 8 a 8.8 piezas por hora hombre (Morales Méndez & Silva Rodríguez, 2016), por mencionar algunos.

En estas investigaciones se reportan los beneficios y las actividades llevadas a cabo dentro de la metodología de SMED, por lo que el problema recae en que no se cuantifica el impacto de esas actividades sobre los beneficios, es decir, cuales son las actividades más importantes o en qué medida esas actividades contribuyen a obtener dichos beneficios.

A lo largo de la metodología de implementación de SMED se desarrollan ciertas actividades que impactan en las actividades de la etapa siguiente, lo cual repercute en los beneficios para la empresa.

De la misma forma, dentro de la literatura de TPM se han identificado ciertos FCE en la implementación, por ejemplo, en Gómez, Toledo, Prado, and Morales (2015) realizaron un análisis de factores para evaluar 31 actividades clave en el proceso de implementación de TPM, y los resultados revelaron nueve categorías: alineamiento estratégico, prácticas de mejora continua, distribución de plantas, mantenimiento autónomo, alineación de equipos, participación de empleados y proveedores, tecnología de punta, desarrollo de tecnología y comunicación con respecto al proceso de desarrollo de TPM, Park and Han

(2001), consideran que un factor clave es la participación de los empleados, ya que el verdadero poder de TPM es utilizar el conocimiento y la experiencia de los empleados para generar ideas para alcanzar las metas y los objetivos deseados, (Ng, Goh, & Eze, 2011) encontraron que los elementos de los recursos humanos junto con el compromiso gerencial, la participación de los empleados, la educación y la capacitación son fundamentales en TPM.

Piechnicki, Herrero Sola, and Trojan (2015) identificaron un conjunto de factores de éxito de TPM y los agruparon en ocho categorías. Como se puede ver, hay una gran cantidad de recursos humanos de FCE para TPM. Sin embargo, Hernández Gómez et al. [27] clasificaron tres categorías de FCE: planificación estratégica, aspectos técnicos y desarrollo de recursos humanos. Como se puede ver, dentro de la literatura, varios autores han identificado una serie de FCE en la implementación de TPM, pero no hay quien relacione estas variables mediante un modelo de ecuaciones estructurales y mucho menos que cuantifique el efecto de esos FCE en los beneficios obtenidos en la implementación de TPM.

1.4 Objetivos de investigación

A continuación, se describen los objetivos que se pretenden abordar en esta investigación

1.4.1 Objetivo General

- Identificar las principales actividades (FCE) en la implementación SMED y de TPM (en cada una de las etapas) en la industria de manufactura de Ciudad Juárez,

1.4.2 Objetivos específicos

- Medir, mediante un modelo de Ecuaciones estructurales, el efecto que tienen las actividades de SMED en los beneficios que se derivan de su implementación dentro de la industria maquiladora de Ciudad Juárez.
- Medir, mediante un modelo de Ecuaciones estructurales, el efecto que tienen las actividades de TPM en los beneficios que se derivan de su implementación dentro de la industria maquiladora de Ciudad Juárez.

1.5 Limitaciones y delimitaciones

Esta investigación se realiza la industria maquiladora únicamente de Ciudad Juárez. Para el análisis de este entorno se utiliza la misma técnica (SEM) para analizar las variables que están involucradas en esos procesos, de modo que faciliten la toma de decisiones. Para lo cual se tienen la siguiente limitacion:

- Los modelos propuestos para el sector de la industria maquiladora, tiene validez únicamente en Ciudad Juárez, México.

2. Fundamentos teóricos

En esta sección se presentan una serie de conceptos teóricos que son la base sobre la cual se han realizado las investigaciones que se reportan en este informe de tesis, por lo que el objetivo no es proporcionar a profundidad el contenido de los mismos, limitándose solamente a explicar sus fundamentos. Algunos de estos conceptos se indican a continuación.

2.1 Elaboración y aplicación de encuestas

Los cuestionarios son uno de los medios más utilizados para recopilar datos y, por lo tanto, muchos investigadores novatos en negocios, administración y otras áreas de las ciencias sociales asocian la investigación con cuestionarios, dada su prevalencia, es fácil suponer que los cuestionarios son fáciles de diseñar y usar; Este no es el caso: se necesita mucho esfuerzo para crear un buen cuestionario que recopile los datos que responden a las preguntas de investigación y atrae una tasa de respuesta suficiente (Rowley, 2014).

Las preguntas de investigación se pueden distribuir a los posibles encuestados por correo postal, correo electrónico, como cuestionario en línea, o cara a cara a mano, estas entrevistas, especialmente las entrevistas estructuradas y semiestructuradas, también hacen preguntas que el encuestado está invitado a responder, pero la característica distintiva esencial de los cuestionarios es que normalmente están diseñadas para completarse sin ninguna interacción directa con el investigador, ya sea de manera personal o remota (Rowley, 2014).

2.1.1 La validez de la información

Una característica importante de la validación del cuestionario es la fiabilidad, ya que para poder medir un concepto determinado mediante un cuestionario válido, la fiabilidad debe ser alta (B. Køster, Søndergaard, Nielsen, Olsen, & Bentzen, 2018). La confiabilidad es un aspecto importante de la validación del cuestionario, ya que estos deben poder reproducir los resultados para que sean válidos (B. Køster et al., 2018). El conocimiento y la actitud son conceptos de personas que normalmente no cambian durante cortos periodos de tiempo, pero los problemas de comportamiento se relacionan con un período específico y, por lo tanto, los elementos que abordan el comportamiento pierden reproducibilidad por el tiempo (Brian Køster et al., 2015).

Hair, Black, Babin, and Anderson (2013) recomiendan encarecidamente que los investigadores siempre confirmen la validez y la unidimensionalidad de sus constructos, incluso si se trata de escalas bien establecidas. La fiabilidad y la validez son cuestiones importantes en una medida creíble de constructos psicológicos, cruciales para la efectividad de cualquier instrumento de investigación (Creswell, 2002).
La fiabilidad de un instrumento debe estar basada en la consistencia con la que pueda generar el mismo resultado en diferentes poblaciones y en diferentes momentos, lo que indica que para tener un cuestionario totalmente valido se requiere realizar pruebas

interactivas con la finalidad de afinar los resultados obtenidos (Nascimento-Ferreira et al., 2016)

2.1.2 Índice de fiabilidad

El alfa de Cronbach es un método popular para medir la fiabilidad, por ejemplo, al cuantificar la confiabilidad de un puntaje para resumir la información de varios ítems en cuestionarios (Christmann & Van Aelst, 2006). Cronbach (1951) cuantifica esta fiabilidad proponiendo un coeficiente (es decir, alfa de Cronbach, que oscila teóricamente entre 0 y 1. Si α está cerca de 0, las respuestas cuantificadas no son confiables en absoluto, y si está cerca de 1, las respuestas son muy confiables, como regla general, si $\alpha \geq 0.8$, las respuestas se consideran confiables. Asimismo, algunos autores proponen otros índices observar si la información obtenida de los cuestionarios es válida o no. Adamson and Prion (2013); (Leontitsis & Pagge, 2007) proponen el índice de fiabilidad de dispersión-media, en el cual, el investigador analiza los ítems del cuestionario mediante la dispersión de la mitad de los mismos. También se propone el índice Kuder-Richardsosn #20 y se le llama K-R 20 porque fue la vigésima fórmula en el cálculo eventual y es la estadística de opción para preguntas de opción múltiple.

2.2 El análisis factorial

El análisis factorial consiste en una colección de procedimientos para analizar las relaciones entre un conjunto de variables aleatorias observadas, contadas o medidas para cada individuo de un grupo, un individuo puede ser una persona, algún otro organismo, un objeto o, en general, cualquier entidad (Cureton & D'Agostino, 2013). El grupo consiste en una clase de tales entidades, por ejemplo, estudiantes de sexto grado, estudiantes universitarios, miembros de un cuerpo legislativo, una especie particular, ratas blancas de una cepa determinada, parcelas de tierra en un bosque o campo, condados en un estado o nación, o cajas, puede ser una población (todas las entidades de la clase definida) o más comúnmente una muestra de dicha población definida. (Cureton & D'Agostino, 2013).

El análisis factorial reduce una gran cantidad de variables en un conjunto más pequeño de variables (también conocidos como factores), establece las dimensiones subyacentes entre las variables medidas y los constructos latentes, lo que permite la formación y el refinamiento de la teoría y proporciona evidencia de validez de constructo de escalas de auto informe (Williams, Onsman, & Brown, 2010). Hay dos clases principales de análisis factorial: análisis factorial exploratorio (EFA) y análisis factorial confirmatorio (CFA), en términos generales, EFA es heurística, en EFA, el investigador no tiene expectativas sobre el número o la naturaleza de las variables y, como sugiere el título, es de naturaleza exploratoria (Williams et al., 2010)

2.2.1 Procedimiento para realizar un análisis factorial

Williams et al. (2010) proponen un protocolo de 5 pasos para principiantes para realizar un análisis factorial, estos se describen a continuación:

1. ¿Los datos son significativos para el análisis de factores?
2. ¿Cómo se extraerán los factores?

El objetivo de la rotación es simplificar la estructura de factores de un grupo de elementos, en otras palabras, altas cargas de ítems en un factor y cargas de ítems más pequeñas en las soluciones de factores restantes (Costello & Osborne, 2005). Existen algunos métodos de extracción comúnmente utilizados en el análisis de factores (Pett, Lackey, & Sullivan, 2003):

- Análisis de componentes primarios (PCA)
- Factorización del eje principal (PAF)
- Máxima verosimilitud
- Menos cuadrados sin ponderar
- Mínimos cuadrados generalizados
- Factorización alfa
- Factorización de imágenes

Los métodos comúnmente usados dentro de la literatura son PCA y PAF y la decisión de cual usar estará en manos del analista (Henson & Roberts, 2006).

3. ¿Qué criterios ayudarán a una extracción determinista de factores?

El objetivo de la extracción de datos es reducir una gran cantidad de elementos en factores. Para producir una unidimensionalidad de escala y simplificar las soluciones de factor, varios criterios están disponibles para los investigadores para más información, consultar (Williams et al., 2010):

- Regla del Porcentaje acumulado de varianza y Eigenvalor > 1
- Prueba de Scree
- Análisis Paralelo

4. Seleccionar un método de rotación

La rotación maximiza las altas cargas de los ítems y minimiza las bajas cargas de ítems, lo que produce una solución más fácil de interpretar y simplificada. Hay dos técnicas de rotación comunes: rotación ortogonal (varimax/quartimax) y rotación oblicua (olbimin/promax).

5. Interpretar y etiquetar

La interpretación implica que el investigador examine qué variables son atribuibles a un factor y le da un nombre o un tema. Por ejemplo, un factor puede haber incluido cinco variables que se relacionan con la percepción del dolor; Por lo tanto, el investigador crearía una etiqueta de "percepción del dolor" para ese factor.

2.3 Modelos de ecuaciones estructurales

El modelado de ecuaciones estructurales (SEM) utiliza diferentes tipos de modos para describir las relaciones entre las variables observadas, con el mismo objetivo básico de proporcionar una prueba cuantitativa de un modelo teórico hipotético por el investigador (Schumacker & G. Lomax, 2010). Nacieron de la necesidad de proporcionar una mayor flexibilidad a los modelos de regresión ya que son menos restrictivos que los modelos de regresión porque permiten la inclusión de errores de medición en las variables de criterio (dependiente) y en las variables de predicción (independiente) (dell'Olio, Ibeas, Oña, & Oña, 2018). Se pueden considerar como una variedad de modelos de análisis factorial que permiten considerar los efectos directos e indirectos entre los factores (dell'Olio et al., 2018).

Más específicamente, varios modelos teóricos pueden probarse en SEM que hipotetizan cómo los conjuntos de variables definen constructos y cómo estos constructos se relacionan entre sí (Schumacker & G. Lomax, 2010). La intención de muchos usos de SEM es estimar estos efectos causales entre las variables, es por esto qué SEM a veces se le conoce como modelado causal (Hoyle, 2012).

Hay dos amplias clases de variables en SEM, observadas y latentes, (ver Figura 5) la clase observada representa sus datos, es decir, las variables para las que ha recopilado puntajes y las ha ingresado en un archivo de datos (Kline, 1998). Otro término para las variables observadas es variables manifiestas. Las variables observadas pueden ser categóricas, ordinales o continuas, pero todas las variables latentes en SEM son continuas, las variables latentes en SEM generalmente corresponden a constructos o factores hipotéticos, que son variables explicativas que se presume que reflejan un continuo que no se observa directamente (Kline, 1998).

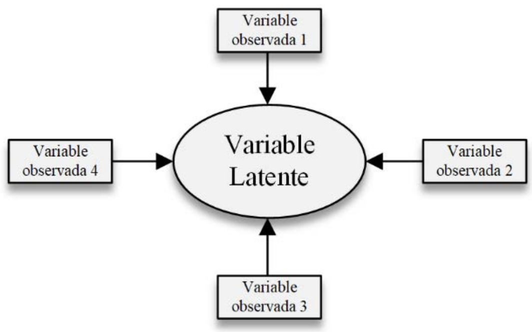

Figura. 2. Variable latente y variables observadas

SEM prueba modelos teóricos utilizando el método científico de la prueba de hipótesis para avanzar en nuestra comprensión de las relaciones complejas entre constructos (Schumacker & G. Lomax, 2010). En la Figura 6 se puede observar un modelo de Ecuaciones Estructurales de tres variables, en donde se tiene una variable independiente (variable exógena), la cual tiene efectos sobre otras y dos variables dependientes (variables endógenas), las cuales reciben efecto de otras (Peng & Wu, 2016).

Las variables latentes 1 y 2 dependen de la variable latente 1, asimismo, la variable latente 3 también depende de la variable latente 2. En este modelo se plantean 4 hipótesis. A las variables latentes dependientes se les asocia un valor de R^2, el cual es el valor de la varianza explicada por las variables independientes.

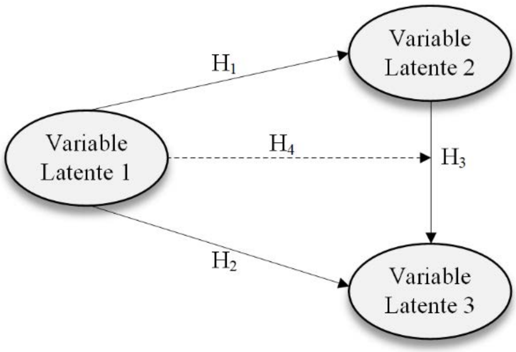

Figura. 3. Modelo de Ecuaciones Estructurales

2.3.1 Software para modelado de ecuaciones estructurales

El modelado de ecuaciones estructurales se entiende fácilmente si el investigador tiene bases en estadística, correlación, regresión y análisis de segmentos; sin embargo, realizar este análisis en modo manual requiere mucho tiempo, por lo que hay muchos programas computacionales para facilitar este análisis. De acuerdo con Lomax and Schumacker (2004), los siguientes son los programas de software para el modelado de ecuaciones estructurales más populares:

- Programas de software que vienen con un paquete de estadísticas: (IBM-AMOS, SAS-PROC CALIS, STATA-SEM y Statistica-SEPATH).
- Programas de software independientes (EQS, LISREL, Mplus y WarpPLS).
- Programas de software gratuitos: (Mx, R-sem y R-lavaan)

La elección del software depende del propósito del análisis SEM y la competencia de las habilidades informáticas del usuario (In’nami & Koizumi, 2013).

2.3.2 Índices de eficiencia de un modelo de ecuaciones estructurales

Antes de realizar cualquier conclusión sobre los resultados que presenta un modelo de ecuaciones estructurales, es importante revisar los índices de eficiencia del modelo, de manera que el modelo no presente colinealidad entre sus variables, asimismo, revisar los coeficientes de los segmentos, entre otros. A continuación se muestran los índices que se reportan en el software utilizado para esta investigación (Hair et al., 2013)

- Promedio de los coeficientes en los segmentos (Average path coefficient, APC)
- Promedio de la R cuadrada (Average R-squared, ARS)

- Promedio de la red cuadrada ajustada (Average adjusted R-squared, AARS)
- Promedio total de los índices de inflación de la varianza (Average block VIF, AVIF)
- Promedio total de colinealidad de los índices de inflación de la varianza (Average full collinearity VIF, AFVIF)
- Índice de bondad de ajuste de Tenenhaus (Tenenhaus GoF, GoF)
- Relación de la paradoja de Simpson (Sympson's paradox ratio, SPR)
- Relación de contribución de la R cuadrada (R-squared contribution ratio (RSCR).
- Índice de supresión estadística (Statistical suppression ratio, SSR)
- Índice de relación y variada no lineal y de causalidad (Nonlinear bivariate causality direction ratio, NLBCDR).

2.3.3 Efectos medidos en modelos de ecuaciones estructurales

Dentro de los modelos de ecuaciones se pueden presentar tres tipos de efectos; efectos directos, efectos indirectos y efectos totales (Bollen, 1987) para indicar las relaciones entre las variables, estos son representados mediante flechas (ver Figura 6).

- Los efectos directos representan cada una de las hipótesis entre una variable independiente (cola de la flecha) y una variable dependiente (punta de la flecha), en el caso de la Figura 6 existen 3 efectos directos, la variable latente 1 tiene un efecto directo sobre la variable latente 2, lo que representa H_1, la variable latente 1 tiene un efecto directo sobre la variable latente 3, lo que representa H_2, por último la variable latente 2 tiene un efecto directo sobre la variable latente 3, el cual representa la H_3.
- Los efectos indirectos se presentan cuando una variable latente tiene un efecto sobre otra, pero este efecto es a través de otra variable, por ejemplo, en el modelo de la Figura 6 se tiene un efecto indirecto, que se da de la variable latente 1 a la variable latente 3 a través de la variable latente 2, es decir, mediante dos segmentos de flecha. El total de este tipo de efecto se calcula mediante la multiplicación de los segmentos involucrados.
- Por último, están los efectos totales, los cuales son la suma de los efectos directos y los efectos indirectos.

3. Metodología

En esta sección se describen los pasos que se siguieron para llevar a cabo los objetivos mencionados en la sección 1.6

3.1 Etapa 1. Elaboración del cuestionario

Como primer paso en esta metodología fue la construcción de los cuestionarios, los cuales se construyeron mediante la revisión de literatura. Se consultaron diferentes bases de datos (Springer, ScienceDirect, EmeraldInsight, entre otras). Ambos cuestionarios cuentan una sección que incluye preguntas de índole demográfica (giro de negocio, años en el puesto, entre otras). Con respecto al cuestionario para TPM, este cuenta con la sección de FCE, en donde las preguntas rondan en torno a las actividades que se realizan durante la implementación de mantenimiento Preventivo, la implementación de TPM, preguntas relacionadas con la cultura laboral, con proveedores, clientes, entre otras. Asimismo, el cuestionario cuenta con una sección de beneficios, los cuales de dividen en beneficios para la empresa, de productividad y de seguridad.

Con frecuencia se incluyen en estos cuestionarios las escalas de Likert (Likert, 1932), que se han convertido en una de las herramientas más populares para medir las propiedades psicológicas (Maeda, 2015). Consiste en una serie de elementos con aproximadamente 4 a 7 puntos o categorías cada una, el análisis puede basarse en elementos individuales o la suma de elementos que forman una escala (Leung, 2011), a menudo ocho o más (Maeda, 2015), cada elemento contiene una raíz (es decir, frase o enunciado) y una escala (es decir, opciones de respuesta), las personas responden a cada número en las opciones de respuesta numeradas (es decir, dos o más puntos) que están etiquetadas, por ejemplo, de totalmente en desacuerdo a totalmente de acuerdo (Maeda, 2015), tal como se ilustra en la Tabla 8. El análisis se realiza sumando o promediando los valores numéricos asignados a cada respuesta (Maeda, 2015),

Tabla 3. Escala de valoración usada

Valor	1	2	3	4	5
Significado	El elemento no está presente	El elemento está poco presente	El elemento está regularmente presente	El elemento casi siempre está presente	El elemento siempre está presente
	El beneficio no se ha obtenido	El beneficio es poco obtenido	El beneficio es regularmente obtenido	El beneficio casi siempre es obtenido	El beneficio siempre es obtenido

3.2 Etapa 2. Aplicación de la encuesta

Los cuestionarios se aplican a personas involucradas dentro de los programas de implementación de SMED y TPM en la industria maquiladora de México; es decir, gerentes, ingenieros, técnicos, supervisores y operadores. Asimismo, se procedió a contactar a cada uno de los gerentes materiales, gerentes de CS, planeadores de materiales y abasto, y en general a aquellos gerentes que tenían relación con la CS y el flujo de materiales a lo largo del sistema de producción.

Primero se hace una cita con personal identificado en las industrias, usando un muestreo de tipo estratificado, ya que solamente interesan industrias que tengan programas de mantenimiento totalmente consolidados, o que tengan más de 10 años de aplicarlo como herramienta en sus sistemas de producción y que puedan demostrarlo mediante registros históricos.

El cuestionario debe responderse en una escala Likert de cinco puntos, tal como se ilustra en la Tabla 8. El uno indica que nunca se realizan las actividades planteadas en el cuestionario o que nunca se obtienen los beneficios, mientras que el cinco indica que siempre se realiza esa actividad o siempre se obtienen esos beneficios.

3.3 Etapa 3. Captura de la información y depuración de la base de datos

Con la información recolectada se elaboró una base de datos dentro del programa SPSS 21®, cada pregunta fue capturada en una columna y cada cuestionario fue ingresado mediante una fila, una vez capturados todos y cada uno de los cuestionarios se procedió a la depuración de la base de datos mediante los siguientes pasos.

3.3.1 Depuración de la base de datos

El primer paso para realizar la depuración de la base de datos es la identificación de valores perdidos y la identificación de valores extremos que provoquen un sesgo en el análisis. Con respecto a los valores perdidos, estos se sustituyeron por la mediana, dado que se está utilizando una escala ordinal tipo Likert de cinco puntos, asimismo si los valores perdidos superan el 10% del total de las preguntas del cuestionario, ese cuestionario se elimina (Hair et al., 2013)

3.3.2 Varianza cero en encuestas

Al momento de contestar a un cuestionario, una persona puede contestar a todas las preguntas con un mismo valor, es decir, que no está comprometido al contestar a dichas preguntas, por lo tanto, no se presenta una variación entre los datos. Para esto, se obtiene la desviación estándar de cada uno de estos cuestionarios, en caso de que la desviación sea menor a 0.50, este cuestionario se elimina (Lourenço & Pires, 2014; Manenti & Buzzi-Ferraris, 2009)

3.4 Etapa 4. Análisis descriptivo de la muestra y de la información

El análisis descriptivo de la información obtenida se realizó en dos diferentes etapas, la primera se refiere a un análisis descriptivo de la muestra en base a la información demográfica que se ha obtenido de la primera sección del cuestionario y en la segunda, se refiere al análisis descriptivo de las valoraciones que se refieren a los factores críticos de éxito en la implementación de SMED y TPM en la industria maquiladora de Ciudad Juárez, México.

El análisis descriptivo de la información se refiere a que para cada uno de los ítems en los cuestionarios se ha obtenido la mediana, como una medida de tendencia central, puesto que los datos han sido en recabados en una escala tipo Likert de 5 puntos y representa solamente valoraciones (Iacobucci, Posavac, Kardes, Schneider, & Popovich, 2015).

Como medida de dispersión se utilizó el rango intercuartílico, el cual se refiere a la diferencia que existe entre el percentil 75 y el percentil 25, un alto valor que indica que no hay consenso entre los encuestados y un valor bajo que indica que si hay consenso entre los encuestados.

3.5 Etapa 5. Validación del cuestionario

Una vez que la información está depurada en la base de datos, entonces el procede a la validación del instrumento y de todas las variables latentes que ahí se tienen.

3.5.1 Alfa de Cronbach, Consistencia interna

El alfa de Cronbach estima la consistencia entre los ítems en una prueba, es decir, la consistencia interna de la prueba (Christmann & Van Aelst, 2006), el cual puede ser estimado en base a la varianza o bien en base a los índices de correlación existente entre los ítems que integran la variable latente que se está midiendo (Adamson & Prion, 2013). en la Tabla 9 se pueden observar los valores que puede tomar el alfa de Cronbach, así como la interpretación del mismo.

Tabla 4. Valores de alfa de Cronbach y su interpretación

α	Interpretación
> 0.90	Excelente
> 0.80	Bueno
> 0.70	Aceptable
> 0.60	Cuestionable
> 0.50	Pobre
< 0.50	Inaceptable

Valores cercanos a 1 indican que esta variable latente tiene una buena fiabilidad, mientras que valores bajos indicarán que esta variable tiene poca fiabilidad y que por tanto los ítems que la integran no están midiendo lo que se pretende medir, Cuando esto sucede, una práctica común en la investigación aplicada es reducir los elementos de una escala para aumentar la fiabilidad de la medida del constructo en esa aplicación específica (Kopalle & Lehmann, 1997; Nunnally & Bernstein, 1994), es decir, el alfa de Cronbach es una función de la correlación media entre los elementos de un cuestionario, se calcula para los elementos k seleccionados, al excluir aquellos elementos que están menos correlacionados, tal procedimiento tiende a aumentar el alfa de Cronbach (Kopalle & Lehmann, 1997).

Dicho lo anterior, en los artículos reportados en este documento, se hace uso de este procedimiento con el objetivo de incrementar la fiabilidad de los constructos de los cuestionarios.

3.5.2 Varianza promedio extraída (AVE), Validez discriminante

Con el fin de establecer la validación del constructo, la mayoría de los estudios de investigación empíricos abordaron esta la tarea al evaluar tanto la validez convergente como la validez discriminante (Drost, 2011).

La validez discriminante es la medida en que un constructo es realmente diferente de otro, un alto grado de validez discriminante proporciona evidencia de que un constructo captura de forma única la propensión del concepto representado que otros constructos no hacen (Shi & Liao, 2013). Con respecto a la medición de la validez discriminante a nivel de ítem, se ha recomendado que un constructo debería compartir más varianza con sus medidas de lo que comparte con otros constructos en el modelo (Faqih, 2016).

3.5.3 Validez Convergente

La validez convergente examina el grado en que una medida se correlaciona con su constructo teórico subyacente (Straub, Boudreau, & Gefen, 2004). La validez convergente existe si un grupo de indicadores está midiendo un factor común (Dai, Chan, & Yee, 2018). Para cumplir con los criterios de validez convergente, Fornell and Larcker (1981) recomendaron que los factores de carga sean mayores a 0.5, la confiabilidad compuesta debe exceder 0.7 y la media de la varianza explicada (AVE) también debe ser mayor que 0.5.

3.5.4 Coeficiente de determinación, validez predictiva

Dentro de los modelos de ecuaciones estructurales se proporcionan varias estimaciones para cada variable latente; estos pueden usarse en informes de investigación para discusiones sobre la confiabilidad, la validez discriminante y predictiva del instrumento de medición, así como la colinealidad general de los coeficientes R-cuadrado, R-cuadrado ajustado y Q-cuadrado por lo que se proporcionan solo para variables latentes endógenas; y reflejan los porcentajes de varianza explicada y validez predictiva asociada con cada una de estas variables latentes, respectivamente.

En todas las técnicas basadas en análisis de regresión se hace uso ampliamente de estos coeficientes de determinación (Lecchi, 2011). A continuación, se describen los tres índices para medir la validez predictiva (Kock, 2015):

- Los coeficientes R-cuadrado se muestran debajo de cada variable latente endógena (es decir, una variable latente que se hipotéticamente afecta por una o más variables latentes), y refleja el porcentaje de la varianza en la variable latente que se explica por las variables latentes hipotéticamente la afectan.
- Los coeficientes R-cuadrado ajustados (Theil, 1958; Wooldridge, 1991) son equivalentes a los coeficientes R-cuadrado, con la diferencia clave que corrigen para falsos aumentos en los coeficientes R-cuadrado debido a los predictores que no agregan valores explicativos en cada bloque de variables latentes.
- El coeficiente Q-cuadrado es una medida no paramétrica calculada tradicionalmente mediante *blindfolding*, se utiliza para la evaluación de la validez predictiva (o relevancia) asociada a cada bloque de variables latentes en el modelo, a través de la variable latente endógena que es el criterio variable en el bloque, los valores aceptables en relación a Q-cuadrado deben ser mayor que cero (Kock, 2015).

3.6 Etapa 6. Formulación de los modelos de ecuaciones estructurales

Los modelos de ecuaciones estructurales representan variables latentes y manifiestas y sus relaciones en un solo modelo estadístico (Evermann & Tate, 2016). La estimación de estos modelos se ha basado tradicionalmente en métodos de análisis de covarianza, usualmente con el estimador de máxima verosimilitud. Sin embargo, el uso del modelo de segmentos de mínimos cuadrados parciales para estimar estos modelos está aumentando en muchas disciplinas (Evermann & Tate, 2016).

La más significativa de las ventajas del SEM es su capacidad de modelar y mostrar simultáneamente las interrelaciones indirectas y directas que existen entre múltiples variables dependientes e independientes (Jenatabadi & Ismail, 2014).

3.6.1 Índices de eficiencia del modelo

Antes de decidir si un modelo de ecuaciones estructurales es bueno, deben estimarse una serie de índices de eficiencia para saber y conocer la idoneidad del mismo. Al igual que en los modelos generados mediante técnicas de análisis de regresión, en los modelos de ecuaciones estructurales también se busca determinar el ajuste del modelo, y para ello se han propuesto varios índices (Kock, 2013), que se describen a continuación.

- Promedio de los coeficientes en los segmentos (Average path coefficient, APC)
- Promedio de la R cuadrada (Average R-squared, ARS)
- Promedio de la red cuadrada ajustada (Average adjusted R-squared, AARS)
- Promedio total de los índices de inflación de la varianza (Average block VIF, AVIF)
- Promedio total de colinealidad de los índices de inflación de la varianza (Average full collinearity VIF, AFVIF)
- Índice de bondad de ajuste de Tenenhaus (Tenenhaus GoF, GoF)
- Relación de la paradoja de Simpson (Sympson's paradox ratio, SPR)
- Relación de contribución de la R cuadrada (R-squared contribution ratio (RSCR).
- Índice de supresión estadística (Statistical suppression ratio, SSR)
- Índice de relación y variada no lineal y de causalidad (Nonlinear bivariate causality direction ratio, NLBCDR).

- Para los índices APC, ARS y AARS, se proporcionan los valores de P. Estos valores de P se calculan mediante un proceso que involucra estimaciones de remuestreo junto con correcciones para contrarrestar el efecto de compresión de error estándar asociado con la adición de variables aleatorias, de manera análoga a las correcciones de Bonferroni (Rosenthal & Rosnow, 1991). Esto es necesario ya que los índices de ajuste y calidad del modelo se calculan como promedios de otros parámetros. Se recomienda que los valores de P para APC, ARS y AARS sean iguales o inferiores a 0,05; es decir, significativo en el nivel 0.05, una regla más relajada sería que los valores de P para APC y ARS solo sean iguales o inferiores a 0.05 (Kock, 2015).

- El índice AVIF aumentará si se agregan nuevas variables latentes al modelo de tal manera que se agregue colinealidad vertical a los bloques de variables latentes, el índice AFVIF aumentará si se agregan nuevas variables latentes al modelo de tal manera que se agregue colinealidad completa al modelo (Kock, 2015). Se recomienda que tanto AVIF como AFVIF sean iguales o inferiores a 3.3, un criterio más relajado (aceptable) es que ambos índices son iguales o menores que 5 (Kock, 2015).
- El índice GoF, conocido como "Tenenhaus GoF" es una medida del poder explicativo de un modelo (Tenenhaus, Vinzi, Chatelin, & Lauro, 2005). definieron el GoF como la raíz del producto entre lo que ellos llaman el índice de comunalidad promedio y el ARS. De acuerdo con Wetzels, Odekerken, xf, der, and van Oppen (2009), propone los siguientes valores para GoF: pequeño si es igual o mayor que 0.1, mediano si es igual o mayor que 0.25, y grande si es igual o mayor que 0.36.
- SPR. El índice SPR es una medida de la medida en que un modelo está libre de las paradojas de Simpson (Pearl, 2003), idealmente, el SPR debería ser igual a 1, lo que significa que no hay casos de la paradoja de Simpson en un modelo; Los valores aceptables de SPR son iguales o mayores a 0.7, lo que significa que al menos el 70 por ciento de las rutas en un modelo están libres de la paradoja de Simpson (Kock, 2015).
- El índice RSCR es una medida de la medida en que un modelo está libre de contribuciones R-cuadrada negativas, que ocurren junto con las paradojas de Simpson (Pearl, 2003). Idealmente, el RSCR debe ser igual a 1, lo que significa que no hay contribuciones R^2cuadrado negativas en un modelo; Los valores aceptables de RSCR son iguales o superiores a 0,9, lo que significa que la suma de las contribuciones R^2 positivas en un modelo representa el 90% de la suma total de las contribuciones absolutas de R^2 en el modelo.
- El índice de SSR es una medida de la medida en que un modelo está libre de instancias de supresión estadística (MacKinnon, Krull, & Lockwood, 2000). Al igual que la instancia paradójica de Simpson, una instancia de supresión estadística es una posible indicación de un problema de causalidad (Spirtes et al., 2000). Los valores aceptables de SSR son iguales o mayores a 0.7, lo que significa que al menos el 70 por ciento de las rutas en un modelo están libres de supresión estadística (Kock, 2015).

El índice NLBCDR es una medida del grado en que los coeficientes de asociación bivariados no lineales proporcionan respaldo para las direcciones hipotéticas de los enlaces causales en un modelo (Kock, 2015). Los valores aceptables de NLBCDR son iguales o mayores a 0.7, lo que significa que al menos el 70 por ciento de las instancias relacionadas con la ruta en un modelo, el soporte para la dirección hipotética de causalidad invertida es débil o menor (Kock, 2015).

En un modelo SEM, es posible representar múltiples vías causales entre los factores medidos o latentes y estimar su efecto relativo hacia una o más variable, además, es posible estimar si uno o más factores pueden actuar como mediadores de tales asociaciones / cadenas causales putativas (Belvederi Murri et al., 2017). También, SEM permite evaluar si otras variables que no están implicadas en un modelo (moderadores) pueden influir en la magnitud o dirección de las asociaciones entre cada factor en el modelo (Belvederi Murri et al., 2017). Para probar las seis hipótesis mostradas en los modelos de ecuaciones estructurales, se utilizó el software WarpPls 5.0®, cuyos algoritmos principales se basan en mínimos cuadrados parciales (PLS), ampliamente recomendado (Kock, 2014).
Los diferentes efectos que existen entre las variables latentes dentro de un modelo de ecuaciones estructurales son:

- Efectos directos
- Efectos indirectos
- Efectos totales

3.6.2 Efectos directos

Se calcularon los efectos directos entre las variables, estos se pueden observar en la Figura 6, los cuales conectan 2 variables mediante flechas, a su vez, cada flecha representa una hipótesis, la cual es asociada a un valor P el cual determina su significancia. Para cada uno de los efectos directos se estimará un valor de una beta (β), la cual puede ser entendida como la intensidad de cambio que existe de una variable latente respecto de la otra (Wetzels et al., 2009). La hipótesis nula $\beta_1 = 0$ contra la hipótesis alternativa que $\beta_1 \neq 0$, así mismo, la dependencia de una variable con respecto a otra, por ejemplo, una variable dependiente es la que está señalada mediante la punta de la flecha y una variable independiente es la variable de la que sale la flecha. Cada hipótesis se probó mediante un nivel de confianza del 95%, así mismo se obtuvo un nivel de significancia representado por β. Del mismo modo se calculó la R^2 la cual representa la varianza explicada de las variables independientes sobre las variables dependientes.

3.6.3 Efectos indirectos y Efectos totales

Los efectos indirectos están mediados por al menos una variable intermedia, se determinan restando los efectos directos del efecto total (Bollen, 1987). Un efecto indirecto se da entre dos variables a través de otras variables llamadas mediadoras, es decir a través de una, dos o más variables, para estos efectos también se calculó un valor-p mediante el cual se concluye si ese efecto es estadísticamente significativo o no, de la misma manera, se calcularon los efectos totales, estos son la suma de los efectos directos e indirectos

3.6.4 Efectos moderadores

Los efectos de moderación conectan variables latentes y enlaces directos; es decir, se refieren a los efectos en los que una variable latente modifica la relación entre un par de variables latentes, el proceso de definición de enlaces modelo a menudo se denomina "definición del modelo interno" (Kock, 2015). Los efectos de moderación están típicamente asociados con moderar hipótesis de causa-efecto o hipótesis de efectos de interacción (Kock, 2015). Los efectos moderadores se presentan mediante líneas punteadas, como se puede observar en la Figura 6, en la hipótesis 4. Este efecto moderador se ha utilizado en diferentes estudios, por ejemplo, para moderar el comportamiento de ciudadanía organizacional sobre el desempeño de profesores (Hakim & Fernandes, 2017), para moderar la capacidad de absorción sobre la orientación empresarial del desempeño internacional de las empresas familiares (Hernandez-Perlines, 2018), para analizar el efecto de los sistemas de información logística sobre la colaboración inter organizacional y el desempeño de las empresas coreanas de transporte marítimo y logística (Bae, 2016), por mencionar algunos.

3.6.5 Tamaño de los efectos

El tamaño de los efectos indican el porcentaje de varianza que explica una variable independiente sobre una variable dependiente (Cohen, 1988; Hayes & Preacher, 2010; Preacher & Hayes, 2004).

3.6.6 Pruebas de multicolinealidad

La multicolinealidad es un problema asociado con el hecho de que los científicos no experimentales observan los valores que toman las variables independientes y dependientes, esto es un marcado contraste con un escenario experimental en el que el experimentador establece los valores de las variables independientes y se observan los valores resultantes de solo la variable dependiente (Fomby, Johnson, & Hill, 1984). En este trabajo se utilizarán los índices AVIF y AFVIF para medir la multicolinealidad entre las variables latentes. En general, no es deseable tener diferentes variables latentes en el mismo modelo que mida la misma construcción subyacente; estos deben combinarse en una variable latente, por lo tanto, los índices AVIF y AFVIF traen nuevas dimensiones que se suman a una evaluación integral de la calidad predictiva y explicativa general de un modelo (Kock, 2015).

4. Resultados

Dado que el objetivo de este informe es presentar las evidencias requeridas para obtener el grado de doctor en la Universidad de La Rioja (España), el cual es defendido por compendio de publicaciones científicas realizadas, entonces, se reportan un total de tres artículos publicados en revistas indexadas en el journal citation report (JCR). A continuación, se muestra el informe en donde se muestran los tres artículos.

En esta sección se presentan las tres publicaciones que se asocian con los factores críticos de éxito en la implementación de SMED y TPM en la industria maquiladora de Ciudad Juárez, México, estas tres publicaciones llevan por título:

- Interrelations among SMED Stages: A Causal Model
- The Effect of SMED on Benefits Gained in Maquiladora Industry
- The Role of Managerial Commitment and TPM Implementation Strategies in Productivity Benefits

4.1 Modelos aplicados a la industria maquiladora de ciudad Juárez, México

En esta sección se revisan dos artículos relacionados con la industria maquiladora de ciudad Juárez, México. Dichos artículos tienen que ver con los factores críticos de éxito en el proceso de implementación de la metodología SMED y de TPM, asimismo, los beneficios que se obtienen al llevar a cabo las actividades de cada una de las etapas de esta metodología

4.1.1 Interrelations among SMED Stages: A Causal Model

Este artículo ha sido publicado en la revista Complexity con un factor de impacto de 4.621 de acuerdo al de acuerdo al último informe del ISI Journal Citation Reports © Ranking: 2016 y se puede localizar en la red bajo en https://doi.org/10.1155/2017/5912940 Volumen 2017.

SMED se ha convertido en una técnica tradicional utilizada en el sector maquilador. Afortunadamente, parece que las empresas manufactureras mexicanas están familiarizadas con las actividades y beneficios de implementación de SMED. Desde esta perspectiva, el objetivo de esta investigación fue medir el efecto de todas las etapas y actividades de SMED en los beneficios que obtienen las maquiladoras mediante el uso de un modelo de ecuaciones estructurales. Los resultados del modelo ayudarían a los gerentes a identificar las actividades críticas desde las triviales, enfocando su atención en aquellas que son relevantes y relevantes.

Para lograr este objetivo, se hizo una revisión de literatura para identificar las actividades que se desarrollan dentro de cada una de las etapas de SMED y de esta manera, crear un cuestionario para recabar información. El cuestionario cuenta con 3 secciones. La sección 1 solicita información demográfica, la sección 2 comprende las actividades de cada una de las etapas de SMES, por último, en la sección 3 se enlistan los beneficios obtenidos de la implementación de SMED.

Para recabar dicha información, se aplicó el cuestionario a las personas involucradas con los cambios de modelo dentro de los diferentes giros (automotriz, eléctrico, electrónico, médico, entre otros) de la industria maquiladora de Ciudad Juárez, México. Desde gerentes, ingenieros, personas dentro del departamento de mantenimiento hasta trabajadores de piso de producción.

Para realizar lo anterior, se creó una base de datos en el software SPSS 21®, en donde cada columna representa una variable y cada fila un cuestionario contestado. Una vez capturada la información, se procedió a depurar la base de datos, al final, el tamaño de muestra quedó en 250 cuestionarios validos cuyas variables tienen un alfa de Cronbach por arriba de 0.7 y no tienen problemas de colinealidad.

Finalmente, las variables latentes se han relacionado para generar un conjunto de seis hipótesis que deberían ser validadas. Dicho modelo fue ejecutado en el software WarpPLS 5® y se ha llegado a las siguientes conclusiones en relación a las hipótesis inicialmente establecidas:

Las variables latentes se han relacionado para generar un conjunto de seis hipótesis que deberían ser validadas. Dicho modelo fue ejecutado en el software WarpPLS 5® y se ha llegado a las siguientes conclusiones en relación a las hipótesis inicialmente establecidas

H_1. Existe suficiente evidencia estadística para declarar que las actividades durante la *Etapa de Identificación* en la implementación de SMED tiene un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Separación*.

H_2. Existe suficiente evidencia estadística para declarar que las actividades durante la *Etapa de Identificación* tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Transformación.*

H_3. Existe suficiente evidencia estadística para declarar que las actividades desarrolladas durante la *Etapa de Separación* tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Transformación*.

H_4. Existe suficiente evidencia estadística para declarar que las actividades durante desarrolladas durante la *Etapa de Identificación* tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Mejora*.

H_5. Existe suficiente evidencia estadística para declarar que las actividades desarrolladas durante la *Etapa de Separación* tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Mejora*.

H_6. Existe suficiente evidencia estadística para declarar que las actividades desarrolladas durante la *Etapa de Transformación* tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Mejora.*

4.1.2 The Effect of SMED on Benefits Gained in Maquiladora Industry

Este artículo ha sido publicado en la revista Sustainability con ISSN 2071-1050 y factor de impacto 1.768 de acuerdo al de acuerdo al último informe del ISI Journal Citation

Reports © Ranking: 2016 y se puede localizar en la red bajo el doi:10.3390/su8121237 en el Volumen 8 número 12

Al igual que el artículo presentado anteriormente, este también se desarrolló dentro de la industria maquiladora de Ciudad Juárez, solo que, en este, se analizan los efectos de las actividades en las diferentes etapas de la metodología de SMED sobre los beneficios de la implementación de la misma.

La metodología seguida para la obtención de la información fue la misma que para el artículo anterior, se aplicó el cuestionario a las personas involucradas con los cambios de modelo dentro de los diferentes giros (automotriz, eléctrico, electrónico, médico, entre otros) de la industria maquiladora de Ciudad Juárez, México. Desde gerentes, ingenieros, personas dentro del departamento de mantenimiento hasta trabajadores de piso de producción. Con la diferencia que en este análisis se utilizó la sección de los beneficios.

En este caso, se analizó una muestra más representativa (373 cuestionarios validos), con los cuales, se creó una base de datos en el software SPSS 21®. Con esta información se realizó un análisis descriptivo de la muestra y de la misma manera, se utilizó el índice de alfa de Chronbach para medir la consistencia interna de cada una de las variables, dicho coeficiente resultó ser mayor al mínimo aceptable. Los valores VIF están por debajo del minino permitido, es decir, no se tiene problemas de colinealidad.

En el modelo se propusieron seis hipótesis las cuales, el modelo fue ejecutado en el software WarpPLS 5® y se ha llegado a las siguientes conclusiones en relación a las hipótesis inicialmente establecidas:

H_1. Existe suficiente evidencia estadística para que declarar las actividades realizadas durante la *Etapa de Identificación* tienen un efecto directo y positivo sobre las actividades llevadas a cabo durante la *Etapa de Separación*.

H_2. Existe suficiente evidencia estadística para declarar que las actividades realizadas durante la *Etapa de Separación* de durante la implementación de SMED tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Transformación*

H_3. Existe suficiente evidencia estadística para declarar que las actividades desarrolladas durante la *Etapa de Separación* en la implementación de SMED tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Transformación*.

H_4. Existe suficiente evidencia estadística para declarar que las actividades llevadas a cabo durante la *Etapa de Transformación* en la implementación de SMED tienen un efecto directo y positivo sobre las actividades desarrolladas durante la *Etapa de Mejora*.

H_5. Existe suficiente evidencia estadística para declarar las actividades llevadas a cabo durante la *Etapa de Transformación* tienen un efecto directo y positivo sobre los *Beneficios de SMED*.

H_6. Existe suficiente evidencia estadística para declarar las actividades llevadas a cabo durante la *Etapa de Mejora* durante la implementación de SMED tienen un efecto directo y positivo sobre los *Beneficios de SMED*.

4.1.3 The Role of Managerial Commitment and TPM Implementation Strategies in Productivity Benefits

Este artículo ha sido publicado en la revista Applied Sciences con ISSN 2076-3417 y factor de impacto 1.689 de acuerdo al de acuerdo al último informe del ISI Journal Citation Reports © Ranking: 2017 y se puede localizar en la red bajo el doi:10.3390/app8071153 en el Volumen 8 número 1153

Este artículo presenta un modelo de ecuaciones estructurales para analizar la relación entre cuatro variables latentes: Compromiso Gerencial, Implementación de TPM, Implementación de PM y Beneficios d Productividad en la industria maquiladora de Ciudad Juárez, incorporando 31 variables observadas. El modelo propone seis hipótesis las cuales se probaron usando información recolectada de 368 encuestas. De esta información, se realizó un análisis descriptivo de la muestra. Las variables latentes fueron validadas haciendo uso del índice alfa de Cronbach con la finalidad de medir la fiabilidad interna, lo cual se puede concluir que existe consistencia dentro de las variables del instrumento. Para conocer la validez predictiva paramétrica de cada una de las variables latentes analizadas, se obtuvo el índice R^2, para la validez predictiva no paramétrica se calculó la Q^2 y para tener una medida de la validez convergente de las variables latentes se ha hecho uso del índice AVE. El modelo de seis hipótesis se ejecutó mediante el software WarpPls 5.0® y en base a los efectos directos que se dan entre las relaciones entre las variables se pueden ha llegado a las siguientes conclusiones:

H_1. Existe suficiente evidencia estadística para declarar que *el Compromiso Gerencial* tiene un efecto directo y positivo sobre *Implementación de TPM*

H_2. Existe suficiente evidencia estadística para declarar que *el Compromiso Gerencial* tiene un efecto directo y positivo sobre *Implementación de PM*

H_3. Existe suficiente evidencia estadística para declarar la *Implementación de PM* tiene un efecto directo y positivo sobre la *Implementación de TPM*

H_4. Existe suficiente evidencia estadística para declarar que el *Compromiso Gerencial* tiene un efecto directo y positivo sobre los *Beneficios de Productividad*.

H_5. Existe suficiente evidencia estadística para declarar que la *Implementación de TPM* tiene un efecto directo y positivo sobre los *Beneficios de Productividad.*

H_6. Existe suficiente evidencia estadística para declarar que la *Implementación de PM* tiene un efecto directo y positivo sobre los *Beneficios de Productividad*.

5 Conclusiones

En este trabajo se han presentado tres modelos de ecuaciones estructurales aplicados en dos sectores diferentes. En base a los resultados obtenidos de los modelos propuestos en el sector de la maquiladora se pueden desprender las siguientes conclusiones:

- El uso de la técnica de SEM ha permitido medir el efecto de las actividades desarrolladas durante la implementación de SMED en las industrias maquiladoras de Ciudad Juárez.
- La etapa más importante dentro de la metodología SMED es la etapa de identificación, lo que implica que si no se hace de una forma correcta, será muy complicado hacer la separación de las mismas.
- Es de vital importancia hacer una clasificación de las actividades internas y externas para prevenir la pérdida de tiempo y por consecuencia, el incremento de los costos.
- Una vez que SMED se ha implementado, es necesario un monitoreo de los cambios de modelo para que de esta forma se puedan seguir detectando áreas de mejora, ya que mejorar los tiempos de cambio de modelo es el principal objetivo y la justificación de un programa de implementación de SMED.
- Las empresas manufactureras deben alentar a los líderes y gerentes de departamento a asumir su responsabilidad y compromiso con TPM. Los gerentes deben promover la participación activa del personal de mantenimiento y comunicar una visión corporativa centrada en la calidad y el mantenimiento del equipo, y entre estos aspectos, deben participar activamente en los proyectos de TPM. Otras dos responsabilidades de los altos directivos son asegurar que el compromiso del personal con TPM esté alineado con la misión corporativa y supervisar el seguimiento de los planes de mantenimiento implementados.
- Los programas de PM deben enfocarse en ajustar y cambiar los componentes antes de que el equipo falle. Además, los gerentes deben promover la prevención de fallas en las máquinas, ya que necesitan comprender el ciclo de vida de los componentes y generar un plan de reemplazo.
- Los gerentes y operadores de TPM deben enfocar sus esfuerzos en programas de PM que consideren el ciclo de vida de los componentes para realizar cambios antes de que fallen las máquinas.
- PM como parte de la implementación de TPM es vital si las compañías aspiran a obtener beneficios de productividad.

6 Conclusions

In this paper, three structural equation models were applied in two different sectors that have been presented. In addition, based on the results obtained from the models proposed in the maquiladora sector, the following conclusions can be presented:

- The implementation of the SEM technique has made it possible to measure the effect of the activities developed during the SMED implementation in the maquiladora industries from Ciudad Juarez.
- The most relevant step in the SMED methodology is the identification stage, which implies that if it is not performed correctly, it will be very difficult to separate them.
- It is vital to classify internal and external activities to prevent the loss of time and consequently, the increasement in costs.
- Once SMED has been implemented, it is necessary to monitor model changes in order that areas of improvement can be detected, since improving model change times is the main objective and justification of a SMED implementation program.
- Manufacturing companies should encourage leaders and department managers to assume their responsibility and commitment towards TPM. In addition, managers should promote the active participation of maintenance personnel and communicate a corporate vision focused on the quality and maintenance of the team, and among these aspects, they should actively participate in TPM projects. Also, two other responsibilities from senior managers are to ensure that the personnel commitment towards TPM is aligned with the corporate mission, as well as supervise the monitoring of the maintenance plans implemented.
- PM programs should focus on adjusting and changing the components before the equipment fails. In addition, managers must promote the prevention of machine failures, as they need to understand the components life cycle and generate a replacement plan.
- TPM managers and operators should focus their efforts on PM programs that consider the components life cycle to make changes before machines fail.
- PM as part of the TPM implementation is crucial if companies aspire to obtain productivity benefits.

Similarly, based on the proposed model in the wine SC, the following conclusions can be stated:

- The implementation of the SEM technique has allowed to measure the effect of the CSF in the SC performance. In this case, the measured variables were: infrastructure, production processes, and SC performance.
- Based on the direct effect from the infrastructure on the production processes, it can be mentioned that, in the wine SC, the production processes depend on a level of 15.5% from the infrastructure installed along the SC.
- Managers should focus on transportation using local infrastructure, because wine is a perishable product that requires special transportation conditions.

- Production processes based on LM will reduce waste (transportation, delays, overproduction, inventory excess) and, therefore, it will generate different types of economic benefits.
- Managers should focus on the Benefits of Transportation and Production Processes to obtain a greater economic benefit in the SC. However, in order to obtain transportation benefits, managers must focus on reducing transportation costs in raw materials and finished products, improved satellite tracking with timely data exchange, and better-quality transportation using distribution centers, outsourcing, and traceability. Finally, those who acquire benefits from transportation help to obtain economic benefits, better cash flows, and greater sales.

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Modelos aplicados a la industria maquiladora de Ciudad Juárez, México

Artículos:

Interrelations among SMED Stages: A Causal Model

The Effect of SMED on Benefits Gained in Maquiladora Industry

The Role of Managerial Commitment and TPM Implementation Strategies in Productivity Benefits

sustainability

MDPI

Article

The Effect of SMED on Benefits Gained in Maquiladora Industry

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Abstract: Nowadays, Single Minute Exchange of Dies (SMED) has achieved great industrial popularity. However, it remains unclear to what extent and how SMED implementation at its different stages benefits industries. To address this gap, this research proposes a structural equation model to quantitatively measure SMED effects. The model has six hypotheses that link SMED stages and benefits. To statistically validate such hypotheses, a questionnaire was administered to 373 Mexican maquiladoras located in Ciudad Juárez, Chihuahua. Results show that before starting SMED implementation process, companies must be appropriately familiarized with their production process. Mainly, manufacturing companies in Ciudad Juárez need to focus their efforts on the SMED planning stage (Step 1) in order to identify important internal production activities and turn them into external activities. In fact, SMED planning stage has direct and indirect effects on subsequent stages and SMED benefits.

Keywords: SMED; lean manufacturing; structural equation model; SMED benefits

1. Introduction

Lean manufacturing (LM), also known as the Toyota Production system (TPS), is one of the most popular techniques for quality and productivity improvement in the automotive industry [1], although it has been also adopted by other industrial sectors, including aerospace, electronics, and services, among others [2]. TPS is the result of many efforts from Toyota to keep updated and compete with Western automobile companies after World War II. LM is a strategy to reduce costs, especially those related to production processes [3].

The principles of LM define the value of product or service with a customer focus. Moreover, LM seeks perfection through continuous improvement and eliminates waste by separating value added activities (VA) from non-value added activities (NVA) [4]. In this sense, LM focuses on different aspects of the production process in order to ensure the value flow.

LM is today conceived as a set of techniques, tools, and philosophies rather than as a strict discipline. According to the LM philosophy, one of the main production systems inhibitors is process inflexibility. Thus, in order to reduce delivery times and stock, and to quickly respond to changes in demand and reach just in time production, companies need to reduce this inflexibility in their production processes [5].

According to Chiarini [3], the most important LM tools to eliminate the different kinds of waste in production are value stream map (VSM), cellular manufacturing, total productive maintenance (TPM), and single minute exchange of dies (SMED). A great amount of literature has addressed the first four tools [6], while information on SMED is a bit scarce.

SMED is a tool developed by Shingo [7] as a proposal to reduce bottlenecks caused by stamping presses in Toyota. By the time SMED was developed, these machines were not working at full capacity and, thus, were not bringing the expected benefits. Nowadays, as Ulutas [8] points out, SMED is one of the many LM tools for waste reduction in production processes, since it offers a fast and efficient way to decrease changeover times. Changeover is the process of converting one line/machine from running one product to another and it is depicted in Figure 1.

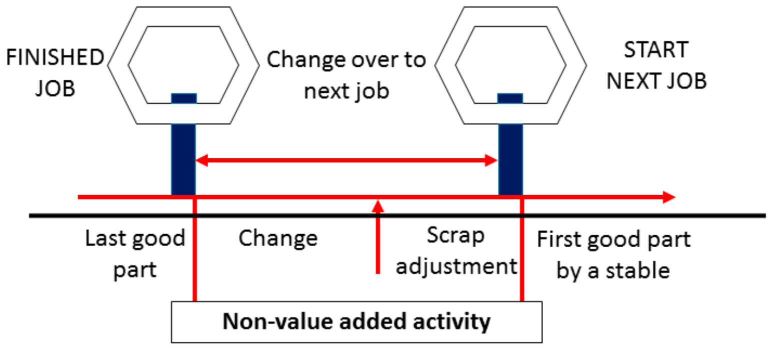

Figure 1. Representation of changeover time [8].

Changeover time is defined as the time needed to set up a given production system to run a different product with all the requirements [9], and they are a typical example of waste, since changeover is a non-added value activity that incurs hidden costs [10]. Therefore, because machines remain inactive during changeover times, this process must be reduced as much as possible [9]. SMED is a practical LM tool that helps maximize the product value by reducing setup times [4].

1.1. Stages of SMED

As previously mentioned, SMED is a tool developed by Shingo [7] to reduce bottlenecks caused by stamping press machines that were not working at full capacity. To solve this problem, Shingo divided SMED implementation into four stages, which are depicted in Figure 2. Each stage includes internal and external activities. Internal activities must be completed when the machine is stopped, whereas external activities have to be completed while the equipment is running.

Stage 0, called *Identification Phase* (preliminary stage), does not yet separate internal and external activities. It is rather a stage to identify and study the problem. At this stage, it is necessary to make some questions regarding the production system. Some of these questions are presented below:

- Is a statistical analysis performed to know time variability of the process [11]?
- Is a statistical analysis performed to know the average process time [11]?
- Is there a detailed analysis of the possible causes of time variability in the process [11]?
- Have operators been interviewed about processes and the machines that they operate [12,13]?
- Are operators' activities being measured with a chronometer [12]?
- Has the company identified activities related to changeovers [14]?

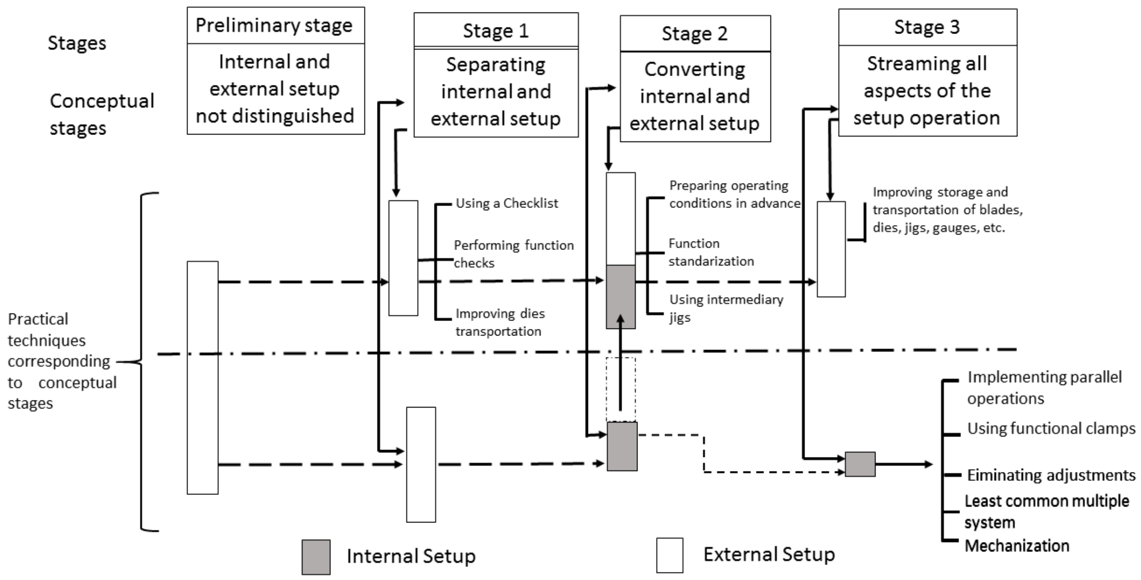

Figure 2. SMED conceptual stages and practical techniques [7]

Stage 1, called *Separation Phase*, focuses on changeover and machine setup activities, since at this stage one must separate internal and external activities. Here, it is important to carry out as many external activities as possible, since they can be performed while the equipment is running. External activities at Stage 1 must be mostly planning operations, which could save between 30% and 50% in setup times.

The main activities performed at this stage are:

- List the main sequential setup operations in order to identify internal activities [15,16].
- List the main sequential setup operations in order to identify external activities [15,16].
- Detect basic problems that are part of the work routine [17].

At Stage 2, called *Transformation Phase*, one must respond to a series of questions that would improve the work plan. Some of these questions are:

- Is the previous work completed before starting changeover [17]?
- Are visual marks used instead of making trial and error adjustments to calibrations [18]?
- Have steps related to search of tools, raw materials, and products been eliminated [18]?
- Have activities been reexamined to make sure none of them has been wrongly assumed as being internal [19]?

In addition, Stage 2 or *Transformation Phase* of SMED implementation, consists in transforming internal activities into external. This implies the following actions:

- Reexamine operations to see whether any activities are wrongly assumed as being internal.
- Find the way to convert these activities into external setup.

Stage 3 or *Improvement Phase* involves streamlining all aspects of the setup, and it includes systematic improvement of all operations. Activities carried out at this stage are:

- Record key setup activities to help improve process time [16,20].
- Train operators to maintain improvement in process time [21].

1.2. SMED Benefits

SMED implementation can be justified by the benefits that it offers to companies. Shingo (1985) pointed out that after company Toyota Amkawa Auto Body Industries K.K. implemented SMED in one of its plants it gained softer production and shorter delivery times. Similarly, authors Musa et al. [12] argued that SMED reduces both setup times and changeover costs, whereas Deros et al. [22] mentioned that this tool increases production flexibility and capacity; it reduces delivery times, inventory levels, and production costs; and, of course, it reduced *setup* times, which help eliminate waste and defects and thus improve product quality.

In general, SMED offers the following benefits:

- Increased productivity [20];
- Eliminates stocks fail due to errors in estimating demand [23];
- Increased work rates and production capacity of machines [24];
- Fewer or no errors in machines setup [24];
- Improved product quality [13,20];
- Increased security in operations [8,13,20,24];
- Improved setup times [9,19];
- Reduced lot size costs [25].

1.3. Research Problem and Objective

In Ciudad Juárez, Chihuahua, the manufacturing industry has been the major source of employment for more than forty years. According to the National Institute of Statistics and Geography (INEGI), in August 2015, the state of Chihuahua catered for 476 manufacturing industries called maquiladoras. Maquiladoras are foreign-owned companies established in Mexico, and they usually import raw material and export finished products to the origin country and others—such as the United States and Canada—using tax benefits from the North American Free Trade Agreement. The maquiladora industrial sector currently employs 341,374 workers in the state of Chihuahua. More specifically, Ciudad Juárez has 315 active maquiladoras representing 66% of the state's total and employing 247,730 workers (72% of the state's total).

Maquiladoras are characterized by high technological capacity and specific employee skills and abilities. These companies are always ready to attend production orders from parent companies located overseas. However, since such production orders usually vary in quantity and product design, changeovers occur frequently. For this reason, SMED has become a traditional technique used in the maquiladora sector. Fortunately, it seems that Mexican manufacturing companies are familiar with SMED implementation activities and benefits. However, because changeovers in machineries occur so often, the effect of SMED is usually unknown and thus rarely analyzed when reporting company benefits.

Currently, structural equation modeling (SEM) has become a popular technique among the engineering sciences to explain dependence among variables in contexts such as Just In Time [26] and Supply Chain [27,28]. From this perspective, the objective of this research is to measure the effect of all SMED stages and activities on the benefits that maquiladoras obtain by using a structural equation model. Results from the model would help managers identify critical activities from trivial ones, thereby focusing their attention on those that are relevant and important.

1.4. Hypotheses

To achieve the proposed objective, we tried to find a dependency measure for each relationship that we proposed between SMED implementation stages and company benefits. To achieve this, we proposed and discussed six working hypotheses. As regards the first hypothesis, it is known that, as part of preventive maintenance programs, manufacturing companies keep record of the activities performed by every machine, its failures, and its effect on product delivery times [29–32]. Similarly, operators are often interviewed to detect and handle equipment failures [33]. When such events are being recorded, SMED implementation becomes much easier when companies must list the sequential activities to identify which are internal and which are external [14,34]. If every activity is identified, categorization is easier [35]. Let us remind ourselves that internal activities must be performed when the machines are stopped, whereas external activities ought to be carried out while machines are still running. In this sense, the first working hypothesis can be proposed:

***H₁*: Activities carried out at the *Identification Phase* of SMED implementation have a direct and positive effect on activities performed at the *Separation Phase.*

If internal and external activities are successfully identified at the *Separation Phase*, it is possible to identify the whole pre-work that must be completed before the machine stops to perform the new setup [36,37]. Similarly, it is possible to identify all tools required for the operation and the visual marks to be used to calibrate machines [38]. Therefore, since activities performed at Stage 1 of SMED implementation have an effect on activities at the *Transformation Phase*, the second working hypothesis can be constructed as follows:

H_2: Activities at the *Separation Phase* of SMED implementation have a direct and positive effect on activities performed at the *Transformation Phase*.

A successful list of external and internal activities also helps recognize critical operations. Activities need to be video recorded to be analyzed and identify unnecessary actions and movements that operators perform when machines are stopped. These actions are a waste of time, which is why they must be eliminated [39]. Similarly, they represent an area of opportunity, since SMED helps evaluate setup methods that operators use to see whether they are appropriate [40,41]. Once unnecessary actions are identified, such methods must be improved and programs must be implemented to train operators in these new activities [42]. All of these tasks imply that activities properly performed at the *Separation Phase* of SMED implementation have an effect on activities performed at the *Improvement Phase*, which enables to propose the third hypothesis:

H_3: Activities performed at the *Separation Phase* of SMED implementation have a direct and positive effect on activities performed at the *Improvement Phase.*

A successful *Improvement Phase* does not merely depend on activities carried out at the *Separation Phase.* The *Transformation Phase* also has an important effect. Let us remind ourselves that, at *Transformation Phase*, operators make sure all tools, equipment, and raw materials are ready and at hand [40,43]. Similarly, they identify instruments to calibrate machines, employ the correct visual marks, and have operation manuals at their disposal in case they need to be consulted [42,44]. Therefore, since these activities are crucial for successful SMED implementation, it is concluded that they have an influence on the *Improvement Phase.* The fourth working hypothesis thus states as follows:

H_4: Activities carried out at the *Transformation Phase* of SMED implementation have a direct and positive effect on activities carried out at the *Improvement Phase.*

SMED must bring a number of benefits that support its implementation. Maintenance and production managers must work hard to reduce changeover times with SMED [39,45]. Thus, companies will obtain notable economic benefits if all setup tools and instruments are always ready and at hand [46], all changeover activities are planned [45], and the correct visual marks are used [47]. Similarly, they would benefit from reduced setup times and errors in production and high-quality products. Moreover, availability and performance of machines will considerably increase, since more time will be dedicated to production [48,49]. From this perspective, the fifth working hypothesis is constructed:

H_5: Activities carried out at *Transformation Phase* of SMED implementation have a direct and positive effect on the *Benefits* gained by manufacturing companies.

SMED benefits are not only obtained from a successful planning stage, since they also depend on properly executed activities [50,51]. In these activities setup methods must be video recorded to analyze and identify unnecessary movements and actions that operators perform in the setup process [44,49,52]. These setup methods must be improved or modified, and the top management department must propose and implement plans and programs to train machine operators [14,35].

Benefits from execution activities mainly include reduced setup costs and small batch production as a result of increased machine productivity and availability [14,53] and increased employee satisfaction [35,54]. Finally, it seems that activities performed when machines are stopped have an important effect on benefits obtained from SMED implementation. Consequently, the sixth working hypothesis is constructed as follows:

***H_6*:** Activities carried out at the *Improvement Phase* of SMED implementation have a direct and positive effect on *Benefits* obtained by manufacturing companies.

As can be seen, six working hypotheses are proposed to assess the effect of SMED implementation in the Mexican maquiladora industry of Ciudad Juárez. These hypotheses are graphically represented in Figure 3.

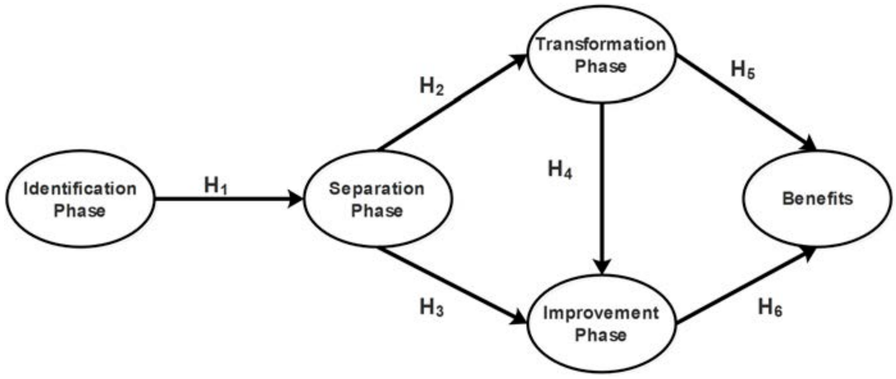

Figure 3. Initial model with hypotheses.

2. Methodology

This section describes the research methodology that was followed to demonstrate the relationships between the three SMED stages and the benefits that companies obtain from its implementation.

2.1. Survey Design

The survey was designed considering SMED activities and benefits reported in the introduction section, and it comprised 22 items divided in two sections. The first section included demographic questions, such as genre, length of work experience, and the industrial sector of the company, while the second section assessed the five latent variables to be studied: the four stages of SMED implementation and SMED benefits. In addition, the questionnaire included as Appendix A a list of the most common SEM-related abbreviations.

The survey was answered with a five-point Likert scale that rated both the frequency at which SMED activities were performed in surveyed companies at the three stages and the extent to which SMED benefits were obtained. Therefore, the lowest value (1) in the scale implied that a SMED activity was not performed or a SMED benefit was not obtained, while the highest value (5) indicated that a SMED activity was always carried out or a SMED benefit was always obtained. Table 1 shows this scale used for subjective assessment of items.

Table 1. Scale used.

Scale	Description
1	Never
2	Rarely
3	Often
4	Very frequently
5	Always

2.2. Data Collection

To collect information, the survey was administered to industries located in Ciudad Juárez (Mexico), which were reached thanks to an address book provided by IMMEX. The sample included employees from all organizational levels—including managers—involved in changeover or equipment maintenance. In addition, the survey was administered as a personal interview to each participant.

2.3. Data Capture and Screening

Data obtained from the survey were captured in a database designed with statistical software SPSS 21® (IBM, Armonk, New York, USA). Each arrow of the database corresponded to an administered survey (case), while each column included one of the 22 items integrating the five latent variables. Then, data were screened to identify missing values and outliers.

Missing values occur when survey questions have not been answered. Sometimes respondents forget to answer a given item, they may not know the answer, or they simply wish not to respond. That said, if there is more than 10% missing values in a survey, such a case is discarded [55]. However, if the percentage is lower, these values are replaced by the median value of items.

After missing values were solved, we estimated the standard deviation of each case. If it was lower than 0.5, the case was discarded, since it implied that almost all items were rated the same, which suggested little commitment to responding to the survey. Finally, as regards outliers, they were replaced by the median of the item, since we dealt with ordinal data.

2.4. Survey Validation

Two indices were used to determine internal validity of each latent variable: the Cronbach alpha [56] and the composite reliability index. The Cronbach alpha index can be estimated based on the variance or correlation indices between items in a latent variable [57]. When the analysis is based on the variance method, the Cronbach index is similar to the index of determination in a simple linear regression, although it is adjusted with the number of items included in the latent variable.

Values of the Cronbach alpha and the composite reliability index vary between 0 and 1. In any analysis, values close to the unit indicate that a latent variable has enough internal reliability, while values close to 0 imply that a latent variable has little internal reliability and its items are not appropriately measured [58]. In this research, we sought values higher than 0.7 in both indices and for all latent variables, meaning that 50% of variance contained in a variable is explained [59].

Other reliability indices used include average variance extracted (AVE), R-squared, Adjusted R-squared, Q-squared, and variance inflation factor (VIF). Being AVE index a measure of convergent validity, Kock [60] recommends values higher than 0.5; however, some other authors argue that a latent variable is reliable if, in its correlation matrix, the AVE square root is higher than any of the correlated indices in the matrix, checked by row and column. When this does not occur, items or variables included in the latent variable have high factor loadings on other latent variables [58].

As for predictive validity, we estimated R-squared and adjusted R-squared indices as parametric measures, and Q-squared as a non-parametric measure. However, note that for more reliable results, R-squared and Q-squared values should be similar. Finally, we looked for collinearity problems in latent variables through VIF, whose value should not be higher than 3.3.

2.5. Structural Equation Model

In this research, we employed the structural equation modeling technique (SEM) to prove the proposed hypotheses and causal relationships (see Figure 1) [61]. In statistics, SEM is used to validate causal relationships between latent variables and is popular in the social sciences and engineering research [62,63], since it finds dependency among latent variables when these are composed by other observed variables [64]. In this study, the structural equation model was executed in software WarpPLS 5.0 (ScriptWarp Systems, Laredo, TX, USA), using partial least squares (PLS) algorithm, which is widely recommended for small samples sizes and non-normal and ordinal data [60]. Moreover, PLS algorithm has been declared as a technique for understanding complex problems and relationships [65].

In addition, six model fit indices were evaluated in the model: average path coefficient (APC), average R-squared (ARS), average adjusted R-squared, average variance inflation factor (AVIF), average full collinearity VIF (AFVIF), and the Tenenhaus GoF. These indices were proposed by Kock [66] and used by Ketkar and Vaidya [67] in the supply chain environment.

On one the hand, *p*-values of APC, ARS, and AARS determined the model's efficiency. The maximum value for these indices was set to 0.05, which implies that inferences were statistically significant at a 95% confidence level, thereby testing the null hypothesis, where APC and ARS equaled 0, versus the alternative hypothesis, where APC and ARS were different from 0. Likewise, it is known in SEM VIF and AFVIF values must be equal to or lower than 3.3 [62], especially in models in which most of the variables are measured through two or more indicators. Finally, in the Tenenhaus GoF index, which is a measure of explanatory capacity [68], values higher than 0.36 [69] are desirable.

The model was executed using WarpPLS 5.0® algorithm with a resampling bootstrap in order to improve values of indices and diminish the effect of possible outliers [62]. In addition, hypotheses were validated by analyzing direct, indirect, and total effects between latent variables. As for direct effects, we estimated values of the beta parameter as a dependency measure, while *p*-values were used to determine statistical significance of hypotheses. Since statistical tests were run with 95% of confidence level, *p*-values had to be lower than 0.05. On the other hand, indirect effects between latent variables occurred through a third our fourth latent variable, also known as mediator. Indirect effects are depicted in the model by more than two paths. Finally, to obtain total effects between latent variables, we added their direct and indirect effects.

3. Results

This section presents results obtained from the model analysis. It is divided in three main sections.

3.1. Description of the Sample

In total, 373 surveys were collected. Figure 4 shows the number of participants for every type of surveyed industry. As can be observed, the automotive industry is the most prominent with 168 questionnaires collected.

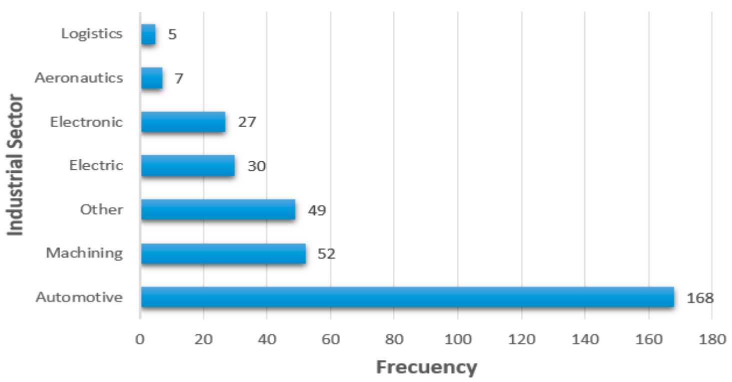

Figure 4. Surveyed industries.

3.2. Statistical Validation of the Survey

Table 2 shows indices employed to analyze latent variables (stages of SMED implementation and SMED benefits). It is important to mention that certain items (activities or benefits) were removed in order to improve such indices. As can be observed, values of R-squared and adjusted R-squared are all higher than 0.2, thus implying that, from a parametric perspective, all latent variables have enough predictive validity. In addition, the Cronbach alpha (internal validity) shows values above 0.7, which demonstrates that the survey is a reliable instrument to collect data. In addition, all AVE values to measure convergent validity are higher than 0.5, while VIF is lower than 3.3 in all latent variables. This demonstrates that there are no collinearity problems. Finally, since Q-squared values are also higher than 0.2, all latent variables have predictive validity from a non-parametric point of view.

Table 3 shows the five latent variables and all the observed variables (survey items) included within them after the reliability analysis (please check survey abbreviations in the Appendix A at the end of the paper). The table also shows combined loadings and cross-loadings of these variables to verify convergent validity. Note that some survey items do not appear in the table, since they were eliminated during the validation process. For instance, item S0 01 at the *Identification Phase* was removed, as it compromised reliability of the latent variable. Finally, note that all *p*-values in the table are lower than 0.01, thereby demonstrating statistical significance of items and convergent validity for latent variables.

Table 2. Survey validation.

Index	*Identification Phase*	*Separation Phase*	*Transformation Phase*	*Improvement Phase*	*Benefits*
R-squared		0.427	0.388	0.365	0.476
Adj. R-squared		0.426	0.386	0.361	0.474
Composite reliability	0.897	0.916	0.868	0.845	0.914
Cronbach's alpha	0.855	0.861	0.797	0.634	0.892
Avg. Var. Extract. (AVE)	0.637	0.784	0.622	0.732	0.571
Full collin. VIF	2.045	2.246	2.021	1.746	2.151
Q-squared		0.428	0.389	0.365	0.478

Table 3. Combined loadings and cross-loading for convergent validity.

Item	*Identification Phase*	*Separation Phase*	*Transformation Phase*	*Improvement Phase*	*Benefits*	*p Value*
S0 02	*0.857*	0.060	−0.006	−0.079	−0.036	<0.001
S0 03	*0.851*	0.045	−0.050	−0.090	0.092	<0.001
S0 04	*0.824*	0.087	−0.050	−0.078	0.140	<0.001
S0 05	*0.716*	−0.190	0.177	0.159	−0.083	<0.001
S0 06	*0.731*	−0.035	−0.052	0.131	−0.141	<0.001
S1 01	0.069	*0.920*	−0.107	−0.015	0.059	<0.001
S1 02	−0.036	*0.924*	−0.031	−0.040	−0.002	<0.001
S1 03	−0.038	*0.808*	0.157	0.064	−0.065	<0.001
S2 01	0.000	0.203	*0.776*	−0.152	0.062	<0.001
S2 02	−0.112	0.067	*0.790*	−0.037	−0.005	<0.001
S2 03	0.109	−0.228	*0.767*	0.095	−0.071	<0.001
S2 04	0.006	−0.043	*0.821*	0.090	0.013	<0.001
S3 01	0.084	−0.095	−0.002	*0.856*	−0.116	<0.001
S3 02	−0.084	0.095	0.002	*0.856*	0.116	<0.001
BE 01	−0.073	0.150	−0.037	0.194	*0.754*	<0.001
BE 02	0.150	−0.121	0.189	0.029	*0.696*	<0.001
BE 04	0.192	−0.089	0.022	−0.061	*0.765*	<0.001
BE 05	−0.089	0.111	0.033	−0.115	*0.779*	<0.001
BE 06	−0.027	−0.171	−0.092	−0.03	*0.783*	<0.001
BE 07	−0.144	−0.002	−0.042	0.039	*0.727*	<0.001
BE 08	−0.076	0.112	−0.040	−0.017	*0.822*	<0.001
BE 09	0.087	−0.007	−0.016	−0.030	*0.714*	<0.001

3.3. Structural Equation Model

Figure 5 shows the analyzed model. Every relationship shows a β value and a *p*-value to determine its statistical significance. In addition, every dependent latent variable includes a R-squared value, indicating their variance explained by independent latent variables. According to values of

APC, ARS, and AARS, the model has acceptable predictive validity since all *p*-values are lower than 0.05. In addition, all values of VIF and AFVIF are lower 3.3, which implies that the model is free from collinearity problems. Finally, since the value of the Tenenhaus GoF index is higher than 0.36, the model is adequate. Once these indices were obtained, results from the model can be interpreted.

Before interpreting the values obtained in the model, it is necessary to validate information. Table 4 illustrates the model fit and quality indices. According to APC, every relationship is valid, since the *p* value is lower than 0.05. In addition, according to ARS and AARS, the model has enough predictive validity, since its associated *p*-value is lower than 0.05. Finally, AVIF and AFVIF values are lower than 3.3, thereby indicating that the model is free from collinearity problems, whereas value of Tenenhaus GoF is large, thus demonstrating that data have good fit to the model.

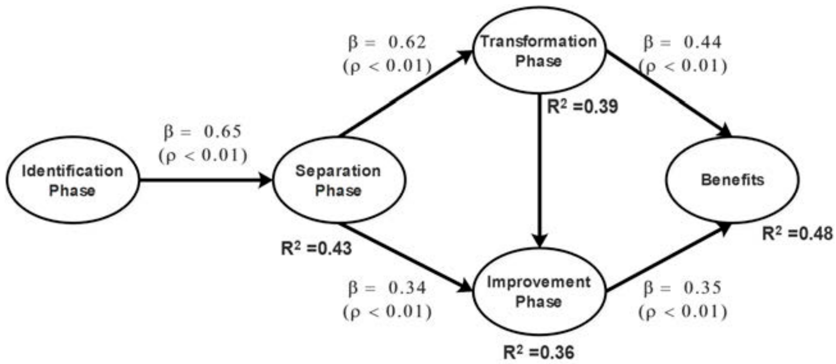

Figure 5. Initial model evaluated.

Table 4. Model fit and quality indices.

Index	Value
Average path coefficient (APC)	0.456, $p < 0.001$
Average R-squared (ARS)	0.414, $p < 0.001$
Average adjusted R-squared (AARS)	0.412, $p < 0.001$
Average block VIF (AVIF) acceptable if ≤5, ideally ≤3.3	1.499
Average full collinearity VIF (AFVIF) acceptable if ≤5, ideally ≤3.3	2.042
Tenenhaus GoF (GoF) small ≥0.1, medium ≥0.25, large ≥0.36	0.526

3.3.1. Direct Effects

Figure 5 shows the evaluated model with the direct effects between latent variables. For direct effects, we interpret the relationships indicated as arrows. In this case, the beta value indicates the dependency value between two latent variables, while the *p*-value indicates statistical significance of the relationship. For instance, the relationship between *Identification Phase* and *Separation Phase* of SMED implementation shows values of $\beta = 0.654$ and $p < 0.01$. This indicates that when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.654 units.

In addition, observe that every dependent latent variable shows a R^2 value, indicating the amount of variance explained by independent latent variables. Since all R^2 values are lower than one, it means that other variables (not included in this model) also affect that dependent latent variable. In this model, two latent variables (*Separation Phase* and *Transformation Phase*) are affected by one independent latent variable, and two more (*Improvement Phase* and *Benefits*) are influenced by two independent latent variables.

Since all direct effects are statistically significant, hypotheses of the final model thus state:

***H_1*:** There is enough statistical evidence to affirm that activities performed at the *Identification Phase* of SMED implementation have a direct and positive effect on activities carried out at the *Separation Phase*, since when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.65 units. Therefore, activities performed at the *Separation Phase* have an effect on the *setup* only if activities at the *Identification Phase* are properly executed.

***H_2*:** There is enough statistical evidence to affirm that activities performed at the *Separation Phase* of SMED implementation have a direct and positive effect on activities performed at the *Transformation Phase*, since when the former latent variable increases its standard deviation by one unit, the latter increases by 0.62 units. Moreover, activities at the *Separation Phase* can explain 39% of the variability of activities at the *Transformation Phase.*

***H_3*:** There is enough statistical evidence to affirm that activities performed at the *Separation Phase* of SMED implementation have a direct and positive effect on activities carried out at the *Improvement Phase*, since when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.34 units. Moreover, there is an indirect effect of 0.204 between these two latent variables, which occurs through activities at the *Transformation Phase*. The total effect is therefore 0.544 units.

***H_4*:** There is enough statistical evidence to affirm that activities performed at the *Transformation Phase* of SMED implementation have a direct and positive effect on activities carried out at the *Improvement Phase*, since when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.33 units.

***H_5*:** There is enough statistical evidence to affirm that activities carried out at the *Transformation Phase* of SMED implementation have a direct and positive effect on SMED *Benefits*, since when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.44 units. Moreover, there is an indirect effect given through activities at the *Improvement Phase*. The effect has a value of 0.115 units; thus, the total effect in this relationship equals 0.555 units.

***H_6*:** There is enough statistical evidence to affirm that activities carried out at the *Improvement Phase* of SMED implementation have a direct and positive effect on economic *Benefits*, since when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.35 units.

3.3.2. Size of Direct Effects

Figure 5 also shows that some dependent latent variables can be explained by one or more independent latent variables. This dependency measure is expressed by the R^2 value, which must be decomposed in the number of independent latent variables that explain a dependent latent variable. For instance, *Separation Phase* is 43% explained by *Identification Phase*, while the remaining 57% may come from other activities, such as the 5S.

Likewise, latent variable *Transformation Phase* is 39% explained by latent variable *Separation Phase*. However, note that *Improvement Phase* is 36% explained by two latent variables, not just one. In this case, *Separation Phase* explains 18% of the variability, whereas *Transformation Phase* explains the remaining 18%. Finally, latent variable *Benefits* is 48% explained by latent variables *Transformation Phase* and *Improvement Phase.* The former is responsible for 27.5%, while the latter explains 20.5%. As can be inferred, activities carried out at the *Transformation Phase* of SMED implementation are key to gaining SMED *Benefits*, since this latent variable has the highest explanatory power.

3.3.3. Indirect Effects

Indirect effects between two latent variables occur through other latent variables, also called mediators. In this research, Table 5 introduces the sum of indirect effects for every relationship, the *p*-values, and the effects size (ES). As can be observed, all *p*-values are lower than 0.01, which proves that all indirect relationships are statistically significant. Indirect effects are obtained by multiplying the direct effects of the involved latent variables. As example, since *Identification Phase* is indirectly related to *Transformation Phase* through *Separation Phase*, the indirect effect is $0.654 \times 0.623 = 0.407$.

Table 5. Sum of indirect effects

	Identification Phase	*Separation Phase*	*Transformation Phase*
Transformation Phase	0.407 (p < 0.001) ES = 0.235		
Improvement Phase	0.358 (p < 0.001) ES = 0.190	0.207 (p < 0.001) ES = 0.113	
Benefits	0.303 (p < 0.001) ES = 0.177	0.463 (p < 0.001) ES = 0.288	0.115 (p < 0.001) ES = 0.072

Note that the strongest indirect effect occurs between *Separation Phase* and *Benefits*. This effect measures 0.463 units, and it shows the highest explanatory power, since it can explain 28.8% of the indirect effects (ES = 0.288). This shows that planning setup operations is key to achieving SMED benefits and goals in mind. The second strongest indirect relationship can be observed between *Identification Phase* and *Transformation Phase* through *Separation Phase.* If the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.407 units. Moreover, *Separation Phase* can explain up to 23.5% of the variability in *Transformation Phase* (ES = 0.235). This shows that information on production processes and equipment maintenance are key to successfully identifying internal and external activities. All indirect relationships can be similarly interpreted.

3.3.4. Total Effects

Table 6 introduces the total effects between latent variables. Based on the p-values, all total effects are statistically significant at a 99% confidence level. Note that, in relationships without indirect effects, total effects equal direct effects, while, in relationships without direct effects, total effects equal indirect effects. The strongest total effects occur between *Identification Phase* and *Separation Phase*, and between *Separation Phase* and *Transformation Phase*. However, in these relationships, total effects are only direct. In contrast, the relationship between *Separation Phase* and *Improvement Phase* has both direct and indirect effects, and the total effect has a value of 0.547. This implies that when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.547 units. Moreover, *Separation Phase* explains up to 29.8% of the variability of *Improvement Phase* (ES = 0.298).

Table 6. Total effects between latent variables.

	Identification Phase	*Separation Phase*	*Transformation Phase*	*Improvement Phase*
Separation Phase	0.654 (p < 0.001) ES = 0.427			
Transformation Phase	0.407 (p < 0.001) ES = 0.235	0.623 (p < 0.001) ES = 0.388		
Transformation Phase	0.358 (p < 0.001) ES = 0.190	0.547 (p < 0.001) ES = 0.298	0.333 (p < 0.001) ES = 0.180	
Benefits	0.303 (p < 0.001) ES = 0.177	0.463 (p < 0.001) ES = 0.288	0.555 (p < 0.001) ES = 0.347	0.347 (p < 0.001) ES = 0.202

Another important total effect is perceived between *Transformation Phase* and *Benefits.* The effect has a value of 0.555, implying that when the first latent variable increases its standard deviation by one unit, the standard deviation of the second latent variable increases by 0.555 units. In addition, *Transformation Phase* explains up to 34.7% of the variability of *Benefits* (ES = 0.347). The remaining relationships can be similarly interpreted.

4. Conclusions

According to data gathered and analyzed from 379 questionnaires administered in Ciudad Juárez, the following conclusions can be drawn regarding SMED implementation in Mexican maquiladoras:

(1) Before implementing SMED in their processes, companies must have adequate information regarding their processes, since activities performed at the *Identification Phase* have a strong effect on activities at *Separation Phase*. Thus, information at the *Identification Phase* is the basis for SMED success.

(2) Companies must pay attention to SMED activities carried out during the *Separation Phase*, since proper identification of internal and external activities has direct and positive effects on activities performed at the *Transformation Phase* and the *Improvement Phase*. Therefore, the planning stage is key to SMED success, since it helps effectively identify internal and external activities and convert many internal activities into external ones. As a result, machines performance is maximized.

(3) Activities carried out at the *Transformation Phase* and *Improvement Phase* are key to obtaining the expected SMED *Benefits*, since these variables explain up to 48% of them. *Transformation Phase* is responsible for 27.5%, while *Improvement Phase* explains 20.2%.

(4) As a LM tool, SMED is extremely useful for the maquiladora industry, since in the manufacturing industry changeovers are recurrent and must be reduced in time.

(5) In this research, we identified many activities required for SMED implementation and several SMED benefits. However, results from the validation process of latent variables showed that not all of these activities or benefits were relevant. Consequently, some of them were removed from the structural equation model.

(6) Based on the highest values of combined loadings shown in Table 3, the most important activity at SMED *Identification Phase* is the use of a statistical analysis to know time variability of the process. The importance of this activity is supported by the fact that companies must always have at hand empirical evidence on the production process before launching any improvement strategy. As for *Separation Phase*, results show that the most important activity refers to listing the main sequential setup operations to identify external operations. In other words, with SMED most activities must be performed while the machine is running, thereby saving time wasted during stoppages.

(6) As regards the *Transformation Phase*, values of combined loadings show that the most important activity is to reevaluate the list made at the *Separation Phase* to make sure that internal or external activities have been correctly classified. In fact, it is important to clearly identify every activity and assess whether it can be executed while the machine is working. Finally, both activities analyzed at the *Improvement Phase* showed the same combined loading value, thereby indicating that they are of equal importance.

(8) Finally, as regards *Benefits* gained from SMED implementation, it seems that setup time improvement is the most important to Mexican manufacturing companies, since it shows the highest value. In fact, improving setup times is the major purpose of and justification for a SMED implementation program.

5. Future Research

The model in Figure 5 shows that variance contained in dependent latent variables is not 100% explained, which implies that other factors can increase it or be the cause of variability. Therefore, in order to increase this value and contribute to the body of knowledge on the effects of SMED implementation in the manufacturing industry, future research will seek to integrate operator training in changeovers and suitability of machinery and equipment as additional latent variables.

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Appendix A. SMED Questionnaire

Single Minute Exchange of Dies (SMED) is a lean manufacturing tool developed for continuous improvement of enterprises. SMED seeks to minimize setup times and changing tools, thereby providing companies with enough flexibility when working with small batch production. This questionnaire aims to identify the critical success factors (CSF) for SMED implementation in the Mexican maquiladora industry. The second objective is to identify the benefits obtained from SMED implementation. Please use the Likert scale (1 to 5) provided to rate SMED activities listed below.

1	2	3	4	5
Never	Rarely	Often	Very frequently	Always

Seniority (years) ☐ 0–1 ☐ 1–2 ☐ 2–5 ☐ 5–10 ☐ More than 10
Industrial sector ☐ Machining ☐ Electrical ☐ Automotive ☐ Aeronautics ☐ Electronics ☐ Logistics ☐ Other ______
Gender ☐ Female ☐ Male
Position ☐ Manager ☐ Engineer ☐ Supervisor ☐ Technical ☐ Operator

Preliminary Stage 0: Changeover Activities

Were the following steps completed before implementing SMED?

	1	2	3	4	5
S0 01 5 s techniques?					
S0 02 Is a statistical analysis performed to know time variability of the process?					
S0 03 Is there a statistical analysis to know the average process time					
S0 04 Is there a detailed analysis of the possible causes of time variability in the process?					
S0 05 Have operators been interviewed about processes and the machines that they operate?					
S0 06 Are operators' activities being measured with a chronometer?					
S0 07 Is there a video recording of process?					
S0 08 Were photographs taken of the process?					
S0 09 Is it necessary to talk to staff to determine any conditions that do not add value?					

First Stage: Separate Internal and External Activities

Were the following steps completed?

	1	2	3	4	5
S1 01 List the main sequential setup operations to identify internal activities					
S1 02 List the main sequential setup operations to identify external activities					
S1 03 Detect basic problems that are part of the work routine.					
S1 04 Is setup of tools, parts and supplies carried out while machines are running?					

Second Stage: Turn Internal Work into External

	1	2	3	4	5
S2 01 Is previous work completed before starting changeover?					
S2 02 Are visual marks used instead of making trial and error adjustments to calibrations?					
S2 03 Have steps related to the search of tools, raw materials, and products been eliminated?					
S2 04 Have activities been reexamined to make sure none of them has been wrongly assumed as being internal?					

Third Stage: Streamlining all aspects of setup and systematic improvement of all operations

	1	2	3	4	5
S3 01 Have key setup activities been recorded to help improve process time?					
S3 02 Have operators been trained to maintain process improvement?					

SMED Benefits

Were the following benefits obtained?

	1	2	3	4	5
BE 01 Increased productivity					
BE 02 It eliminates stocks fail due to errors in estimating demand					
BE 03 Less product deterioration					
BE 04 Increased work rates and production capacity of machines					
BE 05 Fewer or no errors in machines setup					
BE 06 Improved product quality					
BE 07 Increased security in operations					
BE 08 Improved setup times					
BE 09 Reduced lot size costs					
BE 10 Improved operators attitude					
BE 11 Lower training level					
BE 12 Reduced lead times					
BE 13 No waiting times					
BE 14 Small batch production					
BE 15 Flow production					
BE 16 Increased production flexibility					
BE 17 Reduction of setup time into productive time					
BE 18 Reduced inventory levels					
BE 19 Reduced lot production size					
BE 20 Production flow					
BE 21 Reduced bottlenecks					
BE 22 Reduced in process inventory					
BE 23 Quick answer to customer needs					
BE 24 Increased ability to adapt to changing demands					
BE 25 Increased machine utilization rate					

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Research Article

Interrelations among SMED Stages: A Causal Model

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Mexico has received a lot of foreign investment that has brought in a wide range of novel production philosophies, such as Single Minute Exchange of Dies (SMED). Despite its popularity and reported effectiveness, Mexican companies often quit SMED implementation as they consider it challenging. This usually happens when organizations are not familiarized enough with each one of the SMED stages or do not know how they are interrelated. In this article the interrelations among the different SMED implementation stages by means of a structural equations model are analyzed. Data for constructing the model were gathered from a survey administered to 250 employees from the Mexican maquiladora industry. The survey assessed the importance of 14 activities belonging to the four SMED stages. The descriptive analyses of these stages were conducted and integrated into a structural equations model as latent variables, to find their level of dependency. The model was constructed using WarpPLS 5 software, and direct, indirect, and total effects among variables are analyzed and validated. Results from the model revealed that Stage 1 of SMED implementation, known as the *Identification Stage*, has both direct and indirect effects on all the other SMED stages, being the most important stage.

1. Introduction

Many companies respond to the globalization phenomenon by establishing subsidiaries abroad, since this technique allows organizations to reach proximity to target markets. In the case of Mexico, subsidiaries are usually known as *maquiladoras* [1], and they belong to global manufacturing networks that work under the attractive benefits offered by the hosts countries. Some of these benefits include available infrastructure, high training levels, and low production costs [1].

The concept of *maquiladoras*, also known as "twin plants" or "shared production," emerged as a new manufacturing operations model originally put forward in the Mexico-United States border during the 1960s [2], although it later became attractive to numerous European and Asian companies [2]. The maquiladora industry thus became a means to supply manufacturing goods to a larger market and a source of employment for the Mexican people [3], and because of its increasing popularity, the Mexican government established regulations that allowed both domestic and foreign-owned companies to temporally import materials and equipment and export finished products under preferential tariff rates [3].

Many parent companies seek to establish maquiladoras in the Mexican territory to benefit mainly from low labor costs, less restrictive unions and regulations, and greater proximity to target markets [4]. Mexico is thus a facilitator to parent countries since Mexican maquiladoras offer competitiveness and proximity to two major markets, the United States and

Canada [5]. In fact, thanks to the North American Free Trade Agreement (NAFTA) signed by these three countries, many enterprises overseas settle subsidiaries in Mexican land to introduce their products to US and Canadian markets [1].

The maquiladora industry has become so important to Ciudad Juárez, a Mexican border city located in the state of Chihuahua. A report issued in October 2016 claims that, of the 5,012 maquiladoras settled in Mexican territory, 322 are located in Ciudad Juárez, thus representing 6.42% of the national maquiladora industry and generating 263,463 direct maquiladora-related jobs.

Maquiladora sector faces two major problems, rapid production flow and quick introduction of new products into the market, as final customers call for shorter delivery times, low costs, high quality, and highly product customization [6]. Likewise, markets can impose additional exigencies, such as small batch production, which eventually leads to unitary production [7]. Such exigencies are not exclusive to a particular industry, since they have become a global phenomenon [8] and as a response to small batch production challenges, approaches such as *lean* and *pull*—which is a customer-oriented system—have emerged as a means to fulfill the needs of customers without compromising production performance [9]. In this sense, companies must ensure shorter setup times and quick changeovers and both processes are considered to be waste, since machineries, equipment, and operators must stop working, which contributes to increasing manufacturing costs [10]. In this sense, time reduction is a responsibility of lean manufacturing, which aims at waste elimination, especially during setup and changeover times [11].

As a response to last problem *Single Minute Exchange of Dies* (SMED) is defined as a theory and a set of techniques that makes it possible to reduce changeover times to the "single" digits, in other words, to less than 10 minutes [12]. SMED is thus approached as a lean manufacturing tool that helps solve the problems caused by constant equipment changeovers; it improves the *setup* process and reduces the time it takes to change a line or machine from running one product to the next. In fact, setup/changeover time reductions through SMED can reach up to 90% under moderate investments [13]. SMED thus allows companies to respond to market fluctuation, minimize delivery times, reduce waste in setups, and, ultimately, achieve small batch production [14].

1.1. Research Problem and Objective. SMED is a technique widely used by maquiladora companies that is requiring to produce different products in small batches, which forces them to make constant changes in their production lines, making fast setups in machinery to meet these new production orders. Unfortunately, SMED implementation in maquiladoras seldom yields the expected results, and thus companies often quit its application.

Poor results from SMED implementation may appear either because companies are not familiarized enough with the conceptual stages of SMED, or because they do not know how such stages are interrelated; consequently, it is impossible to correctly associate SMED activities with the obtained results or benefits to prioritize the critical operations. To solve this problem, in this article the main research objective is to identify the critical success activities of SMED in the maquiladora industry of Ciudad Juárez. Then, using a structural equations model, we find and quantify the relationships existing among these activities grouped in stages. Results are aimed to support decision makers in the process of identifying key SMED implementation activities and removing unnecessary ones, and this would allow maquiladoras to obtain the expected results.

2. Literature Review and Hypotheses Development

2.1. Literature Review. Companies implement SMED because they can gain certain benefits. Among the SMED benefits reported in the literature, Musa et al. [11] highlighted changeover times minimization and increasing productivity. In this sense, results of their research revealed that *setup* times could be reduced up to 70% thanks to SMED implementation. Similarly, in their study, Ribeiro [15] summarized benefits gained from applying SMED methodology in the production process of plastic and metal components required for the assembly of several kinds of circuit breakers. Beyond the visible economic and technical benefits, authors reported that SMED practices enhanced ergonomic conditions of workstations, achieved setup time reductions ranging from 59% to 90%, and minimized work in process (WIP) of the metal components from 17.05 to 7.74 days, thereby reducing more than 50% of the corresponding costs. In addition, the study states that SMED implementation allowed for WIP cost reduction of over 80% and dramatic minimization of the distance travelled by operators during the changeover process, from 300 m. to 10 m. and less.

Bandyopadhyay [16] reported the impact of SMED on a small-scale automotive industry, where they found that the methodology allowed for 30% of cost reduction and 97 seconds of setup times minimization, thus increasing productivity. Likewise, Yashwant and Inamdar [17] proved that SMED increased utilization rate of four machines that originally worked at a speed 80% below their capacity; in this sense, SMED managed to reduce 50% of setup times and increased production flexibility. Finally, Berk [18] tested SMED applications at two bottleneck setup operations: cast on trap and heat seal. The experiments achieved substantial reduction of cast on trap setup time to 54% and heat seal setup time to 47% as well as significant cost savings at the company level in the assembly lines.

2.2. The SMED Methodology. Previously, SMED was defined as a methodology, and then there are some stages on it. In his work, Shingo [12] presented the four conceptual stages of SMED implementation that make it possible to reduce *setup* and/or changeover times. At the preliminary or zero stage, internal and external work is not yet distinguished, yet Shingo recommends starting by examining the productive process by conducting a continuous production analysis and a work sampling study. It is also advised to video record the whole *setup* or changeover process. In this study, we will refer to the preliminary stage as *Identification Stage.*

In a *setup* process, internal work refers to those activities that must be performed when the machines are stopped, whereas external work includes all those operations that can be performed while the machines are running. At stage 1 of SMED implementation, both internal and external *setup* activities must be clearly distinguished and then separated. This stage guarantees a reduction in *setup* time from 30% to 50% [12]. In this research, we will name stage 1 of SMED implementation the *Separation Stage*.

The second SMED implementation stage, known as the *Transformation Stage*, involves converting as much internal work to external work as possible. In other words, the goal is to perform the greatest amount of work while machines are running. At this stage, Shingo [12] suggests reexamining operations to find whether any steps have been wrongly assumed to be internal.

Finally, at the third stage, all aspects of the *setup* operation must be streamlined and standardized [12] to establish them as the new sequence to be followed. Eventually, all elements ought to be reviewed with an eye toward continuous improvement. In this research, we will refer to stage 3 of SMED implementation as the *Improvement Stage*.

2.3. Hypotheses Development. As mentioned earlier, SMED implementation comprises four conceptual stages. Since the objective of this research is to identify the relationships among these stages, in the following paragraphs we formulate and justify a series of hypotheses in order to study such relationships.

The only means to improve a setup/changeover process is to have enough statistical data of it, because a statistical analysis enables identifying the current status of the problem [19]. In this sense, statistical information may include data on the performed *setup* activities, including order of execution, time needed for making the tool changes, trends, and possible deviations from the process sequence [20]. Knowing this information simplifies decision-making when new methods are to be implemented, since companies become fully aware of the gaps that must be addressed. Other important sources of information are video recordings and the broad range of video recording equipment that is nowadays available allows for easy replay of scenes and frames, which helps companies meticulously analyze and document each SMED activity to detect and eliminate unnecessary work [9].

Once all SMED activities are identified and measured, organizations can move to the identification part to distinguish and separate work that can be performed while the machines are running from work that must be executed when the machines are stopped. Both internal and external work should be identified using a process diagram; otherwise it may be complicated to effectively separate it, and companies would have to stop the machines to ensure the safety of its plant when performing any setup/changeover [21]. To demonstrate that the *Identification Stage* affect the *Separation Stage*, the first working hypothesis is proposed as follows.

H_1. Activities performed at the *Identification Stage* of SMED implementation have a positive direct effect on activities performed at the *Separation Stage*.

Since one of the SMED objectives is to significantly reduce machine stoppage, some setup operations must be executed while it is running, always complying with the corresponding safety norms. After classifying all setup activities at the *Separation Stage*, operators must revise them to be sure the machine can actually be stopped [22]. It is advised to have all necessary equipment and tools at hand to perform the setup but also to remove those instruments that will not be required. Sometimes having too many objects at the workstation can cause accidents [23, 24]. Similarly, companies should use visual signs to signpost every movement required in each setup operation, although this is only possible if internal and external work are appropriately separated. To study the relationship between the *Identification Stage* and the *Transformation Stage* of SMED implementation, the second working hypothesis is proposed as follows.

H_2. Activities performed at the *Identification Stage* of SMED implementation have a positive direct effect on activities performed at the *Transformation Stage*.

Any process improvement methodology using lean techniques such as SMED must take pertinent measurements of the production process [24], since such measurements would allow companies to design an appropriate plan for continuous improvement. For this reason, experts argue that SMED activities to be executed must be measurable and expressed in appropriate units, so that all operators can understand them [25]. In addition, since such operators know best the production process, including changeovers, setups, risks, and opportunity areas, companies should constantly interview them to make sure the adopted measurement methods are appropriate. Also, new improvement proposals must be tape recorded to visualize performed changes [26]. This discussion allows us to assume that there is a significant relationship between setup work analyzed before and after the improvement process. We thus propose the third working hypothesis as follows.

H_3. Activities performed at the *Identification Stage* of SMED implementation have a positive direct effect on activities performed at the *Improvement Stage*.

At the *Separation Stage,* it is important to effectively categorize internal and external setup [27]; otherwise, if an activity is incorrectly classified, companies may be losing valuable time that can actually be productive for the machine [26]. The *Separation Stage* is also key to successful SMED implementation because, if properly conducted, it becomes easier and faster to move toward the *Transformation Stage*, at which companies must convert as much internal *setup* to external as possible [24]. Therefore, to study and test the relationship between the *Separation Stage* and the *Transformation Stage* during SMED implementation, the fourth working hypothesis is proposed.

H_4. Activities performed at the *Separation Stage* during SMED implementation have a positive direct effect on activities performed at the *Transformation Stage*.

Experts argue that if the *Separation Stage* is poorly executed, many opportunity areas will have to be addressed at the *Improvement Stage* [23, 28], yet SMED is a constant

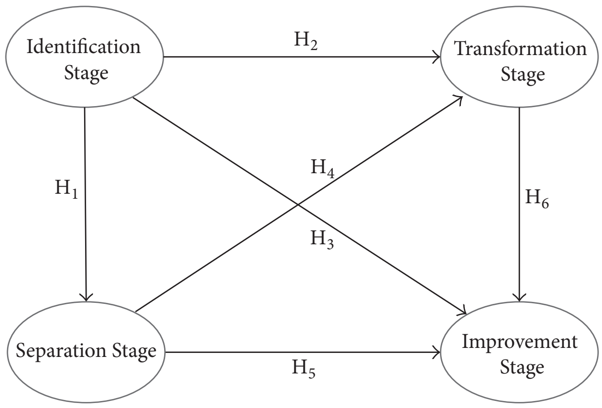

Figure 1: Initial model.

time-improvement seeker, which means that there are always opportunities for minimizing *setup*/changeover times and maximizing machine utilization. However, the *Separation Stage* should never be underestimated and must always be executed in the best possible way from the beginning, even though improvement opportunities may arise later [29]. Considering thus the importance of the first stage of SMED implementation for the correct execution of the third stage, the fifth working hypothesis is proposed.

H_5. Activities performed at the *Separation Stage* of SMED implementation have a positive direct effect on activities performed at the *Improvement Stage.*

As mentioned earlier, the *Transformation Stage* involves revising and reevaluating all the *setup* work previously classified to convert as many internal activities to external as possible. Thus, if any activity or operation is incorrectly classified at the *Separation Stage*, the *Transformation Stage* may be time-consuming [9, 23], since there will be more activities to convert than expected. Undoubtedly, appropriate classification and transformation of activities are the key to a successful SMED program [25]. For this reason, the final working hypothesis of our study reads as follows.

H_6. Activities performed at the *Transformation Stage* have a positive direct effect on activities performed at the *Improvement Stage.*

Figure 1 graphically presents the six working hypotheses integrated in a structural equations model.

3. Methodology

In this research, the following stages were followed to test, validate, and measure the relationships among the four conceptual stages of SMED stated as hypotheses.

3.1. SMED Activities Identification and Survey Design. To identify critical SMED activities, a literature review on SMED implementation is conducted in databases such as ScienceDirect, Springer, and IEEE, among others. Thirteen items in total for the four conceptual stages were identified and used to design a questionnaire and appears in Table 1. The questionnaire was administered to maquiladoras in Ciudad Juárez, namely, to maintenance staff and operators responsible for performing changeovers/setups. The survey was composed of two sections; the first one aimed to gather sociodemographic data, whereas the second section analyzed the four conceptual stages of SMED.

3.2. Survey Administration. To collect data, the survey was administered to Mexican maquiladoras located in Ciudad Juárez, mainly to workers performing changeovers/and setups in companies. The assessment for every item was in a Likert scale [30], because it is a popular method used for studying different aspects of the manufacturing industry, as in risks management in lean manufacturing implementation [31], the incremental contribution of lean management accounting practices [32], and the effects of manufacturing technologies and lean practices on manufacturing operational performance [33]. In this research, we relied on a five-point Likert scale to assess the importance of SMED activities. The lowest scale value (1) indicated that a SMED activity was never performed, whereas the highest value (5) implied that a SMED activity was always performed.

3.3. Data Capture and Screening. Gathered data were captured in a database on statistical software SPSS 21®. Following the data capture, we conducted a screening process to detect both missing values and outliers. Missing values occur when questions were not responded during the survey administration, and on the other hand, outliers reflect that a participant assesses an item with a value different to the used scale. To screen data in each questionnaire, the standard deviation of data was estimated [34] and discarded those surveys that showed a standard deviation below 0.5 [35] and box-plots help to identify outlier.

3.4. Survey Validation. To validate the survey items, seven indices were computed: R-Squared, Adjusted R-Squared, Q-Squared, Cronbach's alpha, Average Variance Extracted (AVE), Average Block Variance Inflation Factor (VIF), and Average Full collinearity VIF (AFVIF). On one hand, R-Squared and Adjusted R-Squared indices were used to measure parametric predictive validity of data [36], whereas Q-Squared is a measure of nonparametric predictive validity [37] whose values should be similar to R-Squared. On the other hand, we computed the Cronbach's alpha as a coefficient of reliability, only accepting values above 0.7.

We also computed AVE as a measure of discriminant validity, only accepting values equal to or higher than 0.5 [38]. Similarly, since VIF and AFVIF indices quantify multicollinearity [39], we looked for values below 3.3 to discard any collinearity problems [38].

3.5. Structural Equations Model. We employed the Structural Equations Modelling (SEM) technique to test hypotheses depicted in Figure 1 and using WarpPLS 5.0® software using factor-based partial least squares (PLS) because it combine precision of covariance SEM-based algorithms under common factor model assumptions with the characteristics of traditional PLS algorithms [38]. Then, we computed six

Table 1: SMED activities at its conceptual stages.

SMED stages	Activity	Description
Identification Stage	S0 02	Is a statistical analysis performed to know time variability of the process?
	S0 03	Is there a statistical analysis to know the average process?
	S0 04	Is there a detailed analysis of the possible causes of time variability in the process?
	S0 05	Have operators been interviewed about processes and the machines they operate?
	S0 06	Are operators' activities being measured with a chronometer?
Separation Stage	S1 01	List the main sequential setup operations to identify internal activities.
	S1 02	Detect basic problems that are part of the work routine.
	S1 03	Is the exchange of tools, parts, and supplies performed with the machine on?
Transformation Stage	S2 01	Is the previous work completed before starting the changeover?
	S2 02	Are visual marks used instead of making trial and error adjustments to calibrations?
	S2 03	Have steps for searching tools, raw materials, and products been eliminated?
	S2 04	Have activities been reexamined to make sure none of them was wrongly assumed to be internal?
Improvement Stage	S3 01	Have key setup activities been recorded to improve process time?
	S3 02	Have operators been trained to maintain improvement in processes?

model fit and quality indices proposed by Kock [38]: Average Path Coefficient (APC), Average R-Squared (ARS), Average Adjusted R-Squared (AARS), Average Variance Inflation Factor (AVIF), Average full Collinearity VIF (AFVIF), and the Tenenhaus Goodness of Fit (GoF), which is an indicator of good model fit to data [40]. For APC and ARS, we expected P values equal to or lower than 0.05 to test average statistical significance of relationships between latent variables at a 95% confidence level. On the other hand, preferred values for AVIF and AFVIF must be below 3.3.

Finally, to validate the model, we estimated and measured three types of effects between latent variables: direct, indirect, and total effects. For each effect, we tested the null hypothesis: H_0: $\beta = 0$ against the alternative hypothesis: H_1: $\beta \neq 0$ at a 95% confidence level. Direct effects appear in Figure 1 as arrows directly connecting two latent variables. In a causal diagram, the arrowhead defines the direction of the causal relationship; in other words, an arrow leading out of latent variable A into latent variable B indicates that the former variable has an effect on the latter, which is also known as the endogenous variable [38]. As regards the other two types of effects, indirect effects occur between two latent variables through mediator variables, whereas total effects are the sum of direct and indirect effects.

4. Results

4.1. Sample Description. After three months of administrating the questionnaire to different maquiladora in Ciudad Juárez, 250 valid questionnaires were collected. Figure 2 introduces a graph reporting the number of maquiladora employees surveyed per industrial subsector. As can be observed, the automobile industry led the research with 104 collected surveys, followed by the machining industry (45 collected surveys) and others (43 surveys). Note that five questionnaires did not report this information. Here it is important to say that 77% of responders were male and only 23% were female. Such results suggest that more male than female employees work in the maintenance departments of Mexican maquiladoras.

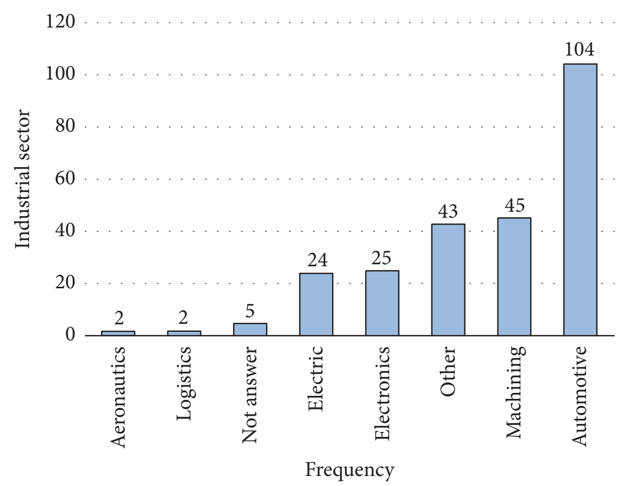

Figure 2: Surveyed industrial subsectors.

Table 2 shows the relationship between surveyed work positions and subsectors, and such information was reported in only 237 of the 250 collected surveys. Note that the automotive industry stood up as the most interviewed subsector with 101 collected questionnaires. As regards job positions, results from the analysis show technicians as the leading job position (99 respondents representing 40.5%), followed by operators (66 collected surveys). The remainder of the sample included engineers, supervisors, and mangers, providing 45, 25, and 5 surveys, respectively.

4.2. Survey Statistical Validation. As mentioned in the methodology section, we computed seven indices to validate latent variables. R-Squared, Adjusted-R-Squared, and Q-Squared indices indicated that variables had enough predictive validity from both parametric and nonparametric

Table 2: Contribution of work position and industrial subsector.

Job position	Industrial sector							
	Machining	Electrical	Automotive	Aeronautics	Electronics	Logistics	Other	Total
Manager	0	3	1	0	0	0	1	5
Engineer	2	7	27	0	3	1	5	45
Supervisor	4	3	13	0	2	0	3	25
Technician	22	4	40	0	15	1	14	96
Operator	17	6	20	2	4	0	17	66
Total	45	23	101	2	24	2	40	237

Table 3: Survey validation.

Index	Identification Stage	Separation Stage	Transformation Stage	Improvement Stage
R-Squared		0.443	0.390	0.366
Adj. *R*-Squared		0.440	0.385	0.358
Composite Reliability	0.885	0.911	0.855	0.823
Cronbach's alpha	0.837	0.851	0.774	0.770
Avg. Var. Extract. (AVE)	0.609	0.774	0.597	0.699
Full Collin. VIF	2.012	2.108	1.701	1.566
Q-Squared		0.444	0.392	0.368

Table 4: Model fit and quality indices.

Index	Value
Average Path Coefficient (APC)	0.343, $P < 0.001$
Average *R*-Squared (ARS)	0.400, $P < 0.001$
Average Adjusted *R*-Squared (AARS)	0.395, $P < 0.001$
Average Block VIF (AVIF): acceptable if ≤ 5, ideally ≤ 3.3	1.819
Average Full Collinearity VIF (AFVIF): acceptable if ≤ 5, ideally ≤ 3.3	1.847
Tenenhaus GoF (GoF): small ≥ 0.1, medium ≥ 0.25, large ≥ 0.36	0.517

perspectives. Likewise, since the Cronbach's alpha reported values above 0.7 in all cases, we concluded that all latent variables possessed enough internal validity. Also, AVE values, all above 0.5, validated convergent validity, whereas VIF values, all below 3.3, discarded collinearity problems within them. These indices and their values are shown in Table 3.

4.3. Structural Equations Model. Table 4 lists the six model fit indices computed to validate the model (see methodology section). Since *P* values of APC, ARS, and AARS were below 0.05, we concluded at a 95% confidence level that the model had enough predictive validity. Similarly, AVIF and AFVIF values. both below 3.3, discarded collinearity problems among latent variables, whereas the Tenenhaus GoF revealed a good model fit to data, since its value was above 0.517. In conclusion, all model fit and quality indices proved that the model could be analyzed in the full confidence and its interpretations would be valid.

4.3.1. Direct Effects. Direct effects appear illustrated in Figure 3 using arrows directly connecting two latent variables and represented as hypotheses. Every direct effect was associated with a beta (β) value and a *P* value; the former represented the dependency, expressed in standard deviations, between the two involved latent variables. For instance, we found that latent variable *Identification Stage* had a positive direct effect on latent variable *Separation Stage*, where $\beta = 0.67$ and $P < 0.01$. This means that when *Identification Stage* increases its standard deviation by one unit, the standard deviation of *Separation Stage* increases by 0.67 units; moreover, this relationship was statistically significant at a 95% confidence level, since its *P* value was lower than 0.05, even lower than 0.01. All direct effects between latent variables depicted in Figure 3 are similarly interpreted.

Every dependent latent variable was also related to an *R*-Squared value (R^2) that specified its amount of variance explained by independent latent variables. In the case of latent variable *Separation Stage,* its variability was explained 44.3% by *Identification Stage*, since $R^2 = 0.443$. However, sometimes more than one independent variable explain variability in a dependent variable. In this sense, the model's evaluation revealed that *Improvement Stage* was explained in 36.6% by the remaining three independent latent variables: *Identification Stage* (9.9%), *Separation Stage* (14.1%), and *Transformation Stage* (12.6), since $R^2 = 0.366$. Table 5 introduces all R^2 values found in the model. The portion

Table 5: Effect sizes of direct effects.

	Identification Stage	Separation Stage	Transformation Stage	R-Squared
Separation Stage	ES = 0.443 ($P < 0.01$)			0.443
Transformation Stage	ES = 0.309 ($P < 0.01$)	ES = 0.222 ($P < 0.01$)		0.390
Improvement Stage	ES = 0.258 ($P < 0.01$)	ES = 0.191 ($P < 0.01$)	ES = 0.126 ($P < 0.01$)	0.366

Table 6: Hypotheses validation.

Hypotheses	Independent variable	Dependent variable	β	P value	Conclusion
H_1	Identification stage	Separation stage	0.665	$P < 0.001$	Accept
H_2	Identification stage	Transformation stage	0.302	$P < 0.001$	Accept
H_3	Separation stage	Transformation stage	0.382	$P < 0.001$	Accept
H_4	Identification stage	Improvement stage	0.196	$P < 0.001$	Accept
H_5	Separation stage	Improvement stage	0.263	$P < 0.001$	Accept
H_6	Transformation stage	Improvement stage	0.249	$P < 0.001$	Accept

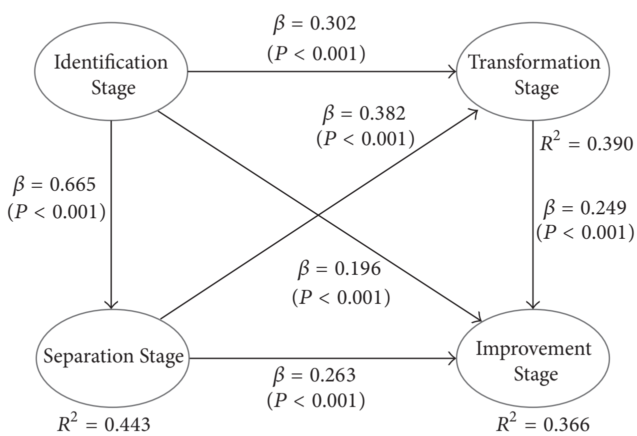

Figure 3: Final model.

of R^2 value explained by an independent latent variable in a dependent latent variable is known as effect size and is rounded up to the third significant decimal.

Since all the P values associated to β values were lower than 0.05, we computed the following standardized equations for relationships between latent variables:

$$\begin{aligned} &\text{Separation Stage} \\ &\quad = 0.665 \text{ Identification Stage} + \text{Error} \\ &\text{Transformation Stage} \\ &\quad = 0.302 \text{ Identification Stage} \\ &\qquad + 0.382 \text{ Separation Stage} + \text{Error} \\ &\text{Improvement Stage} \\ &\quad = 0.196 \text{ Identification Stage} \\ &\qquad + 0.263 \text{ Separation Stage} \\ &\qquad + 0.249 \text{ Transformation Stage} + \text{Error}. \end{aligned} \quad (1)$$

For hypotheses proposed in Figure 1 and tested in Figure 3, the following conclusions can be stated based on obtained β and P values shown in Table 6. For each hypothesis, the independent latent variable, the dependent latent variable, the β value, the P value associated, and the conclusion appear. The β value indicates that when the independent variable increases by one unit its standard deviation, the dependent variable increases that value and the P value indicates that all relationships are statistically significant; therefore, all hypotheses are accepted.

4.3.2. Indirect Effects. There were three indirect effects between latent variables through one or more mediator variables. The obtained P values proved that all indirect effects were statistically significant at a 95% confidence level. In that sense, it was found that activities performed at *Identification Stage* have the highest indirect effect on activities performed at *Improvement Stage*, since the indirect effect showed a higher value than its direct effect (0.314 versus 0.20) which is given through mediator variables *Separation Stage* and *Transformation Stage*. As for the effect size, it can be concluded that activities conducted at *Identification Stage* explained up to 15.9% of the variability of activities performed at *Improvement Stage*, since ES = 0.159.

In addition, the effect between *Identification Stage* and *Transformation Stage* given through *Separation Stage* whose value P is less than 0.001 indicating that the effect is significant with an effect size of 0.141 means that the *Identification Stage* variable explains 14.1% of the *Transformation Stage* variable. Finally, the effect between Separation Stage and Improvement Stage through the mediator variable called Transformation Stage shows a P value equal to 0.016. Thus, it can be concluded that the effect is significant and effect size is 0.051, indicating that the variable defined as Separation Stage explains 5.1% of the variable called Improvement Stage.

4.3.3. Total Effects. Total effects between two latent variables are the sum of their direct and indirect effects. Table 7 presents the total effects found in the evaluated model. Three

Table 7: Total effects.

	Identification Stage	Separation Stage	Transformation Stage
Separation Stage	0.665 ($P < 0.01$) ES = 0.443		
Transformation Stage	0.556 ($P < 0.01$) ES = 309	0.382 ($P < 0.01$) ES = 0.222	
Improvement Stage	0.510 ($P < 0.01$) ES = 0.258	0.358 ($P < 0.01$) ES = 0.191	0.249 ($P < 0.01$) ES = 0.126

total effects equaled direct effects, since in such relationships no indirect effects were found. Likewise, all P values were low enough to validate total effects at a 95% confidence level. As for the magnitude of effects, the largest total effect reported concerned latent variables *Identification Stage* and *Separation Stage*.

In the relationship between activities performed at the *Identification Stage* and those performed at the *Transformation Stage*, indirect effects represented 45.68% of total effects, although these effects were a bit lower than the direct effect (0.254 versus 0.302). Similarly, between activities performed at the *Identification Stage* and those performed at the *Improvement Stage*, total effects equaled 0.510 units and 0.196 came from the direct effect and 0.314 from the indirect effects. In this case, the latter were significantly higher than the former, representing 61.56% of the total effects. Similar interpretations were formulated for the remaining relationships.

5. Conclusions and Industrial Implications

In this research, we proposed six hypotheses to relate the four conceptual stages of SMED. By means of a structural equations model we demonstrated that all these relationships were statistically significant. Such findings allow us to discuss the following conclusions and industrial implications:

(1) We found the highest total effect in the relationship between the *Identification Stage* and the *Separation Stage* and these findings imply the following:

   (a) Prior to SMED implementation, companies must be fully aware of the current situation of setups and changeovers times required, since this would allow them to determine the current problem status. Information can be obtained measuring time and operations' movements, video recording the setup/changeover operations, and establishing a sequence for such operations as mentioned by Adanna and Shantharam [41].

   (b) All tools necessary to perform the setup/changeover must be at hand before the machines are stopped; otherwise companies may compromise machine availability and the production flow. A similar recommendation is given by Ferradás and Salonitis [9]

(2) In the relationship between *Identification Stage* and *Improvement Stage*, the indirect effects were visibly higher than the direct effect and that findings demonstrate that activities conducted at other stages are important mediator variables for a successful SMED implementation planning. These findings are in concordance with Choo et al. [19], because improving a setup/changeover process is important to have enough statistical data of it.

   In addition, the results show that to make a successful setup the video recording of the activities of SMED to detect those that are not adding value is necessary. As mentioned in Ferradás and Salonitis [9], video recordings allow for easy playback of scenes and frames, which helps companies to meticulously analyze and document each SMED activity to detect and eliminate unnecessary work.

(3) The relationship between *Identification Stage* and *Transformation Stage* showed the highest indirect effect, which demonstrates that making the appropriate classification of internal and external *setup* prevents from wasting time and increasing costs, as mentioned in Rodríguez-Méndez et al. [21].

(4) The most crucial stage in SMED implementation is the *Identification Stage*, which explains 44.3% of the variability in *Separation Stage*, the highest R^2 value found (see Figure 3), and this mean that if activities are not correctly identified, they will not be able to separate in an appropriate way and consequently cannot minimize the setup. This statistical finding is similar to reports from Rodríguez-Méndez et al. [21].

(5) Once SMED has been implemented, maquiladora companies need to monitor the setup/changeover once more, including timing and video recording, to identify the current status of the setup/changeover and detect potential improvement areas, thereby continuing with the continuous improvement cycle, as mentioned in Azizi and Manoharan [26].

(6) New machines must replace old ones as soon as their lifecycle ends. In this sense, some major decision criteria for evaluating and selecting machinery include time required for performing setups/changeovers and maintenance needs, since the processing times can vary due to the aging or deterioration of the machines [42]. In production, machines may be available from preventive maintenance, periodic repairs, or breakdowns. Maintenance activity is one of the best equipment operations management to enhance machine efficiency and improve product quality, as mentioned by Yang [43].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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The Role of Managerial Commitment and TPM Implementation Strategies in Productivity Benefits

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Featured Application: The findings in this research allow managers to know quantitatively the importance of preventive maintenance in an adequate performance of total productive maintenance and productivity benefits in a production system, allowing them pay attention on those activities that are more important.

Abstract: The present research proposes a structural equation model to integrate four latent variables: managerial commitment, preventive maintenance, total productive maintenance, and productivity benefits. In addition, these variables are related through six research hypotheses that are validated using collected data from 368 surveys administered in the Mexican manufacturing industry. Consequently, the model is evaluated using partial least squares. The results show that managerial commitment is critical to achieve productivity benefits, while preventive maintenance is indispensable to total preventive maintenance. These results may encourage company managers to focus on managerial commitment and implement preventive maintenance programs to guarantee the success of total productive maintenance.

Keywords: TPM; implementation; managerial commitment; productivity benefits

1. Introduction

In current industrial scenarios, waste in production processes is frequent, usually the result of the lack of skills of both operators and maintenance staff, not enough machinery available, and issues with work tools [1]. Other types of waste include machinery downtime, not utilizing talents, damaged machinery, and rejected parts, among others [2].

To increase competitiveness, manufacturing companies seek to reduce the activities that add no value to a product but generate cost, and in this sense, one way of reducing waste is to adopt a lean approach. The lean manufacturing (LM) approach aims to reduce the amount of non–value-added activities in the production process, although it also has reported benefits at the administrative level [3]. LM relies on several tools to achieve its goal, and total productive maintenance (TPM) is one of the most important, because it helps companies to minimize waste, such as damaged machinery and unplanned work, and it encourages the development of production plans that prevent machine overload [4].

Furthermore, TPM can be defined as an approach that rapidly improves production processes through employee involvement and empowerment [5]. Nowadays, in the restless and uncertain global business environment, well-managed organizations strive to improve their capabilities by operating profitably; in other words, TPM is a tool that, if correctly implemented, can help businesses reach this goal [6].

Currently, TPM is a successful tested LM tool for planning the maintenance of organizational activities, which involve operators and maintenance staff working together as a team [7]. In this sense, TPM is associated with human resources, and it integrates equipment maintenance in the production process to increase machine availability, as well as adding commercial value to the organization [8].

Also, TPM aims to keep production equipment in proper working condition to prevent breakdowns that eventually delay the production process or make unsafe workplaces, thus TPM is one of the main operational activities in quality management systems [8]. Additionally, TPM emphasizes proactive and preventive maintenance to maximize operational production machinery efficiency and decrease the roles of the production and maintenance departments by empowering operators [8]; it improves organizational competitiveness and comprises a powerful and structured approach to changing employee mentality and, consequently, the organizational culture. This also includes employee involvement at all hierarchical levels in all company departments [9]. In addition, it involves member alignment to improve corrective actions associated with safety [7].

Similarly, TPM not only focuses on machine efficiency, but also is an opportune area for continuous improvement, looking for an ideal relationship between people and machines. In other words, successful organizations must be supported by effective and efficient maintenance plans as a competitive strategy [10]. However, production systems are not the only places where TPM can be applied, because other service-based systems need to be in optimal operating condition as well, such as medical equipment and instruments [11].

Because of the benefits that TPM brings to the industrial environment, one of the main academic and industrial concerns is to find its critical success factors (CSFs). Identifying CSFs allows company managers and administrators to prioritize the activities that ensure TPM success. Also, many studies have reported the key activities involved in these TPM factors [12–15] as well as the obtained benefits [16,17]. However, the relationship between these success factors and company benefits have not been clearly defined.

In addition, it is observed that there is an academic and industrial interest to identify the CSFs of TPM, as well as the activities that integrate them [12–15,18,19]. Similarly, there are several reports associated with the obtained benefits from proper TPM implementation in production systems [16,17,20]; however, the problem is that there are not enough studies that link CSF with obtained benefits, and as a result, it has not been determined which CSFs are crucial for obtaining specific desired benefits.

Kamath and Rodrigues [21] state that the CSFs may be different from one industrial sector to another and that findings cannot be generalized. For example, Chlebus, et al. [22] report on activities associated with TPM in a mine, and Ahuja and Khamba [23] report on manufacturing industries in India. In Mexico there are currently 5518 maquiladora industries with manufacturing and export services, and in Chihuahua state there are 510, and these amount to 9.25% of the national total. Of those 510 in Chihuahua state, Ciudad Juárez has 332, which is 65.10% of the state, directly employing 268,761 workers [24]. Those maquiladora companies are characterized by a high technological level that requires a lot of maintenance services, and there are not enough studies indicating which are the CSFs of TPM and the benefits gained in that industrial sector.

Because the relationship between CSFs for TPM and gained benefits is currently an interesting research area, this paper presents a structural equation model that associates three CSFs: managerial commitment, TPM implementation, and PM implementation, which are related to productivity benefits. In addition, findings in this paper will help managers identify the most significant activities to have a successful TPM implementation and guarantee its benefits.

The purpose of this research is to quantify, through a structural equation model, the impact of managerial commitment, the implementation process, and the plans and programs executed as CSFs for TPM on productivity benefits gained, and it is validated using information from the maquiladora industry in Mexico.

The rest of this paper is organized as follows: Section 2 provides a brief introduction to concepts related to managerial importance in TPM implementation and its benefits, Section 3 presents the research hypotheses that link the studied variables, Section 4 describes the research methodology, Section 5 reports the research findings, and, finally, Section 6 shows the research conclusions and industrial implications.

2. Maintenance and Concepts

2.1. Critical Success Factors of TPM

CSFs are relevant performance areas that help companies reach desired goals (e.g., TPM goals) [25]. The literature on TPM addresses a large number of CSFs for TPM implementation. For instance, Park and Han [17] consider that a key factor is employee involvement, since the true power of TPM is using employee knowledge and experience to generate ideas to achieve the desired goals and objectives. On the other hand, Ng, Goh and Eze [12] found that human resources elements along with managerial commitment, employee involvement, education, and training are fundamental in TPM.

In their research, Piechnicki, et al. [26] identified a set of critical TPM success factors and grouped them into eight categories: education and training, teamwork, planning and preparation, senior managerial commitment, resistance to change, change of culture, employee involvement, monitoring results, and effective communication; as can be seen, there are a lot of CSF human resources for TPM. However, Hernández Gómez et al. [27] classified three categories for CSF: strategic planning, technical aspects, and human resources development. That list supports the importance of human resources in TPM success.

In a recent study, Gómez, Toledo, Prado, and Morales [14] performed a factor analysis to evaluate 31 key activities in the TPM implementation process, and the results revealed nine critical success factors: strategic alignment, continuous improvement practices, plant distribution, autonomous maintenance, equipment alignment, employee and supplier involvement, cutting-edge technology, technology development, and communication regarding the TPM development process. This research reveals that top managers must be highly committed to TPM, since they provide the necessary implementation resources. Similarly, operators are equally necessary to detect and prevent errors before failures occur; this approach to equipment maintenance is called preventive maintenance, which is another critical success factor of TPM.

2.2. Preventive Maintenance

Preventive maintenance (PM) is defined as a set of activities performed at certain times in a planning horizon to extend the equipment life cycle and keep it in satisfactory working condition, and to increase overall system reliability and availability [28]. Such activities are a part of maintenance programs and attempt to minimize the risk of unplanned equipment downtime. According to its nature, PM includes inspection, cleaning, lubrication, adjustment, alignment, and component replacement for machinery and tools in a production process [28].

Those tasks play a vital role in any production process, as they preserve equipment operating under desired long-term specifications [29]. Also, PM has a positive impact on cost, quality, and delivery performance [30], because it minimizes quality costs by keeping the equipment in the best working condition through proper maintenance programs that guarantee a high rate of compliant products [31].

Currently there are studies that reveal the importance of PM in production systems. For example, Eti et al. [32] make an association between the cost of PM and increased reliability of machinery and equipment; Anis et al. [33] propose a plan to relate PM program activities with batch size for production lines to minimize the time lost due to stoppages associated with maintenance. Shrivastava et al. [34] state that product quality is not the responsibility of one department, but preventive maintenance and calibration and adjustments in machinery and equipment are essential to guarantee products with specifications required for clients. Finally, given that PM requires stopping machines and equipment continuously, Fumagalli et al. [35] recommend adequate orchestration of maintenance plans with product delivery commitments in the production system.

All of the above show the importance of PM as a work culture focus for conservation of machinery, and this has industrial and academic interest.

2.3. TPM Benefits

TPM critical success factors guarantee important benefits. According to Willmott and McCarthy [16], they provide opportunities to develop suitable strategic plans for the company's capabilities, infrastructure, and human resources to support integration between the operation and maintenance departments, and improve business relationships with customers and suppliers. Similarly, Ma et al. [36] reported that TPM increases production system efficiency, brings social benefits, and promotes management systems in production departments. On the other hand, Gupta, Vardhan, and Haque [13] mention that TPM increases employee morale and skills, improves the use of technology, and enhances equipment working conditions and customer satisfaction. Additionally, successful industries that implement TPM increase their overall equipment efficiency (OEE) by 30%, and some have increased OEE by 95%.

In addition, Ng et al. [37] found that TPM minimizes machine downtime, increases employee motivation, and minimizes accidents. Likewise, Rodrigues and Hatakeyama [38] argue that companies can increase daily production rates with their current productive capacity and workforce if they implement TPM strategies; however, the researchers also claim that many companies tend to spend little time on equipment maintenance and struggle to empower operators to help maintain their equipment.

3. Hypotheses and Literature Review

The goal of TPM is to maximize equipment effectiveness by continuously improving availability and preventing failures, but this cannot be achieved without managerial support [39] and employee involvement. Therefore, participation by all employees promotes a preventive maintenance approach based on motivation management and voluntary small group participation [40]. Also, TPM concepts entail a long-term commitment to planning, especially from senior managers, and usually initiates as a top-down exercise, but it can only be successfully implemented as "bottom-up" participation [7]. From this perspective, the operator commitment, performance, and morale reflect the managerial commitment to TPM [41]. In conclusion, managerial commitment is the most essential factor in TPM implementation [39], which is why the first hypothesis in this research can be proposed as follows:

Hypothesis 1. *Managerial commitment has a positive and direct effect on TPM implementation.*

TPM initiates with senior managers, since they have the power to implement the necessary organizational changes and formulate the required plans, strategies, and policies, which must be aligned with corporate objectives. Also, the maintenance manager is responsible for the effective performance of TPM activities and setting the basic policies and objectives to be reached through a carefully designed plan [39]. Similarly, senior managers should remove the obstacles that interfere with TPM plans and implementation, and they must make sure that such plans are aligned with the company's short- and long-term goals [42]. In other words, because TPM is based on error prevention, it is important to rely on effective preventive maintenance techniques. PM must be aligned with managerial preferences and priorities in a production system, since that guarantees workers' acceptance, and it always must be focused on preventing accidents or failures [43]. Therefore, the second hypothesis in this research can be presented as follows:

Hypothesis 2. *Managerial commitment has a positive and direct effect on PM implementation.*

The main TPM characteristics are economic efficiency, preventive maintenance, improved maintenance capacity, and employee involvement [44]. As Nakajima [45] argues, the main goal in the TPM implementation stage is to increase equipment efficiency through specific techniques, including autonomous maintenance, where employees improve their skills and help to maintain their equipment. From this perspective, it is claimed that PM is part of the organizational culture and an essential component of TPM; that is, there must be an error and failure prevention program to ensure TPM. Therefore, the third hypothesis in this research can be proposed as follows:

Hypothesis 3. *PM implementation has a positive and direct impact on TPM implementation.*

As Nakajima [46] points out, the main TPM objectives are to improve productivity, increase management efficiency, and eliminate the six types of production waste. In addition, managerial commitment, along with clear and common goals and visible results, creates a responsibility shared by a team and leads to fewer interruptions and higher reliability levels [47]. Therefore, TPM relies on long-term managerial commitment to increase equipment efficiency and efficacy in order to offer the expected benefits [9]. As a result, the fourth hypothesis in this research can be presented as follows:

Hypothesis 4. *Managerial commitment has a positive direct effect on productivity benefits.*

TPM implementation can minimize waste and redundant work, and increase company profitability and image, which guarantee competitiveness for a company [39]. Likewise, TPM improves OEE, productivity, safety, and quality, and minimizes equipment life cycle costs [48]. In addition, implementing a TPM approach leads to increased efficiency and work quality; minimizes customer complaints, accidents, and internal waste [49]; and improves delivery performance, stock turnover and employee morale, productivity, and performance [50]. Therefore, the fifth hypothesis in this research is proposed as follows:

Hypothesis 5. *TPM implementation has a positive direct effect on productivity benefits.*

PM is a scheduled activity usually initiated under certain statistical parameters (e.g., average time, usage) that determine when maintenance actions are necessary before entering the risk zone (where the probability of random equipment component failure increases) [51]. In addition, PM must help prevent unplanned equipment downtime and maximize system availability by keeping equipment in proper working condition and improving its availability. PM includes scheduled tasks, such as supervision of hardware replacement and control before the equipment ends its life cycle. Due to these PM activities, there is a direct impact on the production system [52]; the sixth hypothesis in this research can be presented as follows:

Hypothesis 6. *PM implementation has a positive direct effect on productivity benefits.*

Figure 1 illustrates the established relationships between the studied variables relating CSFs for TPM and gained benefits.

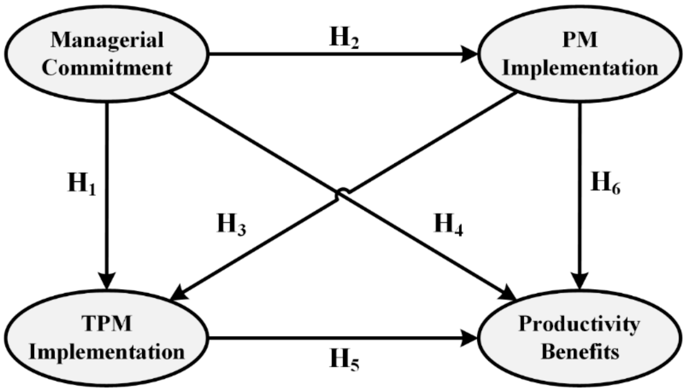

Figure 1. Initial model. TPM, total productive maintenance; PM, preventive maintenance.

4. Materials and Methods

4.1. Stage 1: Survey Design

In order to validate the model in Figure 1, a survey instrument to gather data was designed. As a matter of fact, designing the survey included reviewing works similar to this research to identify which activities (items) integrate each latent variable (e.g., CSF for TPM and productivity benefits). The previous studies were collected from multiple databases, including ScienceDirect, Springer, and IEEE, among others. This literature review represented validation of the survey's rationale [53] and Table 1 illustrates the CSF for TPM (activities) and productivity benefits gained that were identified.

Table 1. Total productive maintenance (TPM) critical success factors and productivity benefits.

Latent Variable	Items
preventive maintenance (PM) Implementation [51,54]	preventive maintenance as a quality strategy. maintenance department committed to prevention and operator support. report the maintenance actions performed on the equipment. disclose statistics of the maintenance records. easy access to equipment maintenance records. record the quality generated by the equipment. identify causes of machine failures and report the statistics.
TPM implementation [4,26,27]	proper education and training of maintenance staff. follow-up and control of the maintenance program. commitment from managers and maintenance staff. managerial leadership in TPM execution. leadership from production and engineering departments in TPM execution. maintenance staff leadership in TPM execution. communication between production and maintenance departments. knowledge of critical machine systems. TPM focused on the life cycle of machine systems, parts, and components. purchase of machines and equipment based on TPM.
managerial commitment [26,27,39]	department leaders embrace their TPM responsibilities. top managers lead TPM execution. meetings are held between production and maintenance departments. top managers promote employee participation and encourage preservation of the work team. top managers develop and communicate a quality- and maintenance-centered vision. top managers are directly involved in maintenance projects.
productivity benefits [15,37]	elimination of productivity losses. increased equipment reliability and availability. reduction of maintenance costs. improved final product quality. decreased spare parts inventory costs. improved corporate technology. improved response to market changes. development of corporate competitive skills

Next, the identified activities were used to develop a preliminary survey integrated by three sections: sociodemographic information, activities of critical success factors for TPM and PM, and productivity benefits.

4.2. Stage 2: Survey Administration

The final questionnaire was given to TPM practitioners in the Mexican manufacturing industry: senior managers, engineers, technicians, supervisors, and operators. In order to select the sample, first a stratified sampling technique was followed; that is, companies with fully consolidated maintenance programs (10 years of implementation or more) that could corroborate such information through equipment maintenance records were identified and considered.

The survey was answered with a five-point Likert scale, as seen in Table 2, through face-to-face interviews. The lowest value on the scale (1) indicated that an activity was never performed or a productivity benefit was never obtained, whereas the highest value (5) indicated that an activity was always performed or a productivity benefit was always obtained. Also, experienced personnel who were interviewed recommended other possible responders, then the snowball sampling technique was implemented.

Table 2. Survey scale.

Value	1	2	3	4	5
interpretation	never	rarely	regularly	frequently	always

4.3. Stage 3: Data Capture and Screening

The collected data were registered in a database using SPSS 24®; the columns represented the survey items and the rows cases or questionnaires. Then, the database was screened by performing the following operations:

- The standard deviation was calculated; if the value was lower than 0.5, that case was removed, since all the items had a similar value [55].
- The missing values were identified; if a questionnaire had 10% or more missing values, it was discarded [56]. On the other hand, for questionnaires that had less than 10% of missing values, such values were replaced with the median in the item [57].
- Outliers were identified by standardizing each item; extreme or atypical observations with an absolute standardized value greater than 4 [58,59] were replaced by a median value in the item.

4.4. Stage 4: Survey Validation

Once the data were evaluated, the 4 latent variables were tested by estimating the following indices proposed by Kock [60]:

- R-squared and adjusted R-squared for the predictive validity of the survey from a parametric perspective; only values over 0.2 were acceptable.
- Q-squared for the predictive validity of the survey from a nonparametric perspective; acceptable Q-squared values, and their R-square values, must be greater than 0.
- Cronbach's alpha and compound reliability index for internal variability of the latent variables; internal validity can be estimated based on the variance or correlation index between the items of a latent variable [61], and acceptable values must be greater than 0.7.
- Average variance extracted (AVE) for the convergent validity of the items in the latent variables; acceptable values must be greater than 0.5.
- Average block variance inflation factor (VIF) and average full collinearity VIF (AFVIF) for the collinearity of the items in the latent variables; acceptable values must be less than 3.3.

4.5. Stage 5: Structural Equation Model

The 4 latent variables were integrated into a structural equation model (SEM), as illustrated in Figure 1, with 6 research hypotheses. In addition, the SEM was tested using partial least squares (PLS), which is widely accepted in multiple disciplines [62]. Also, the greatest advantage of an SEM is its ability to model and illustrate, at the same time, the direct and indirect interrelations between multiple dependent and independent latent variables, because the latent variables have different roles, as dependent and independent, in this research. Likewise, SEMs are reliable even using nonnormal data, small samples, or ordinal data [63].

The research hypotheses shown in Figure 1 were tested using WarpPLS v.6.0® software (ScriptWarp Systems, Laredo, TX, USA, 2017), which is based on PLS; it is widely recommended by Kock [64], and some PLS applications can be found, for instance, in Midiala Oropesa, et al. [65], who modeled the effects of Kaizen in an industrial context, or in García-Alcaraz, et al. [66], who modeled the effects of Just in Time (JIT) in the manufacturing industry.

The model was tested with a 95% reliability level, implying that the *p*-values of the parameters had to be lower than 0.05. Before interpreting the SEM, 6 efficiency models and quality indices were calculated, proposed by Kock [60]:

- Average path coefficient (APC): statistically validates the hypotheses in a generalized way. The *p*-value must be less than 0.05.
- Average R-squared (ARS) and average adjusted R-squared (AARS): measure the model's predictive validity. Acceptable *p*-values for ARS and AARS must be less than 0.05. The null hypotheses to be tested are APC = 0 and ARS = 0 against the alternative hypotheses, where APC $\neq$ 0 and ARS $\neq$ 0.
- Average variance inflation factor (AVIF) and average full collinearity VIF (AFVIF): measure the level of collinearity between the latent variables. The acceptable value must be less than 3.3.
- Tenenhaus goodness of fit (GoF): measures the explanatory power of the model. The GoF value must be greater than 0.36.

4.5.1. Direct Effects

The direct effects in the model were evaluated and are illustrated in Figure 1 by arrows directly connecting two latent variables, where each arrow represents a hypothesis. In addition, each effect has a β value and a *p*-value; β expresses dependency in standard deviations between an independent and a dependent latent variable, whereas *p*-value is for the hypothesis test where the null hypothesis is $\beta_1 = 0$, which is tested against the alternative hypothesis, $\beta_1 \neq 0$ [60]. Additionally, R^2 for the dependent variables was estimated as a coefficient that shows the amount of variance in a dependent latent variable that is explained by an independent latent variable.

4.5.2. Indirect Effects and Total Effects

In SEMs, indirect effects occur between 2 latent variables through other latent variables, known as mediators. Indirect effects also have *p*-values to determine whether they are statistically significant or not. On the other hand, total effects in a relationship are the total direct and indirect effects; total effects also have associated *p*-values.

Finally, for each effect (direct, indirect, or total), the effect size for decomposition of R-squared was estimated when 2 or more independent latent variables influenced a dependent latent variable.

4.5.3. Sensitivity Analysis

Frequently, the relationship between the latent variables is not explained enough by β values and it is necessary to know different scenarios for them. In this research, for every relationship or hypothesis in Figure 1, the probability of occurrence for 2 scenarios is analyzed when each variable occurs independently with low and high values. A third scenario represents the probability of the combination of both variables in a hypothesis when they occur simultaneously, while a fourth scenario is about the probability that the dependent variable will occur in a high or low scenario because the independent variable has occurred in a high or low scenario (a conditional probability). Since the latent variables are standardized, values greater than 1 represent high scenarios in a latent variable, while values less than 1 represent low scenarios for a latent variable.

In this research, scenarios with low values are represented by a minus sign (−) and scenarios with high values are represented by a plus sign (+). In the same way, the probability of simultaneous or simultaneous occurrence of scenarios between 2 variables (low or high) is represented by an ampersand (&). Finally, the conditional probability of occurrence of a scenario in a dependent latent variable because the scenario for the dependent variable has happened is represented by "If."

In addition, since the automotive industrial sector in this geographic context is one of the most representative in previous surveys reported by Mendoza-Fong, et al. [67], that sector is compared with other sectors to find significant differences among them, so that a model is executed for the automotive sector and a model is rejected for others, and differences in β are tested.

5. Results

5.1. Sample Description

After four months of survey administration, 368 questionnaires were collected. Table 3 lists the surveyed industrial sectors and the respondents' job positions. As can be observed, most of the sample is from the automotive industry (74 technicians, 41 operators, 32 engineers, 22 supervisors, 1 manager, and 2 other job positions).

Table 3. Industrial sector vs. job position.

Job Position	Industrial Sector						
	Aeronautics	Electrics	Automotive	Electronics	Medical	Other	Total
technician	0	21	74	29	7	11	142
operator	1	4	41	11	10	12	79
engineer	3	6	32	7	4	1	53
supervisor	1	9	22	8	2	6	48
manager	0	1	1	1	2	1	6
other	0	0	2	0	0	1	3
total	5	41	172	56	25	32	331

Also, only 331 respondents provided information. Most of the respondents are maintenance technicians or operators; together the categories represent 66.67% of the sample. Such results imply that the data collected from the survey were obtained from people directly involved in equipment maintenance.

5.2. Survey Statistical Validation

Table 4 presents the estimated coefficients or indices for the latent variables. Based on these indices, we concluded that the latent variables have enough parametric and nonparametric predictive validity, internal validity, and convergent validity. Similarly, according to the VIF values, the latent variables are free from internal collinearity problems. Consequently, because the latent variables passed the validation process, they were integrated into the model and evaluated.

Table 4. Survey validation.

Index	Managerial Commitment	TPM Implementation	PM Implementation	Productivity Benefits
R-squared	–	0.628	0.407	0.382
adj. R-squared	–	0.626	0.405	0.377
composite reliability	0.942	0.939	0.902	0.956
cronbach's alpha	0.926	0.928	0.873	0.948
average	0.729	0.608	0.569	0.732
variance inflation factor	2.560	2.804	1.982	1.499
Q-squared	–	0.630	0.409	0.381

5.3. Structural Equation Model

Table 5 shows the model fit and estimated quality indices in the model. Based on the APC, ARS, and AARS values, the model has enough predictive validity. Similarly, the VIF and AFVIF values demonstrate that the model is free from collinearity problems, whereas GoF shows that the model fits the data. According to these data, the effects between the variables can be interpreted.

Table 5. Model fit and quality indices.

Index	Value
average path coefficient (APC)	0.368, $p < 0.001$
average R-squared (ARS)	0.472, $p < 0.001$
average adjusted R-squared (AARS)	0.470, $p < 0.001$
average block VIF (AVIF); acceptable if ≤ 5, ideally ≤ 3.3	1.912
average full collinearity VIF (AFVIF); acceptable if ≤ 5, ideally ≤ 3.3	2.211
tenenhaus goodness of fit (GoF); small ≥ 0.1, medium ≥ 0.25, large ≥ 0.36	0.558

5.3.1. Direct Effects

Figure 2 presents the model results once the latent variable coefficients, model fit, and quality indices were estimated. As can be inferred from the *p*-values, all direct effects or direct relationships between the latent variables are statistically significant with a 95% reliability level. Table 6 summarizes the conclusions regarding the research hypotheses. All of the research hypotheses were accepted, since they are statistically significant.

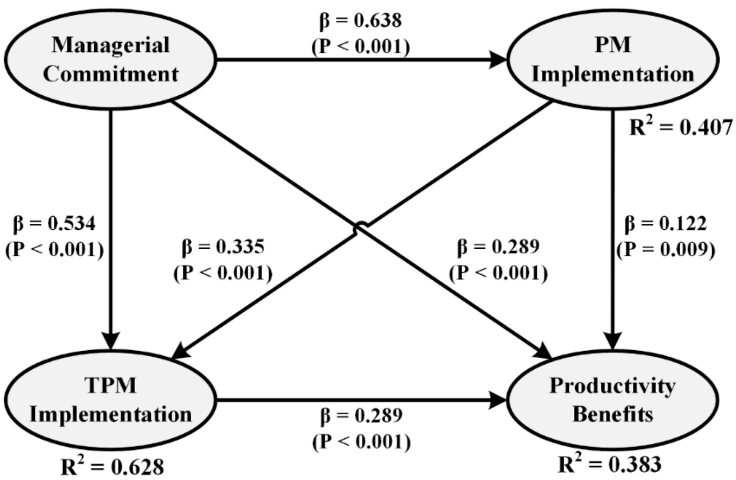

Figure 2. Evaluated model.

Table 6. Hypothesis validation.

Hypothesis	Independent Variable	Dependent Variable	β	*p*-Value	Conclusion
H1	managerial commitment	TPM implementation	0.534	<0.001	accepted
H2	managerial commitment	PM implementation	0.638	<0.001	accepted
H3	PM implementation	TPM implementation	0.335	<0.001	accepted
H4	managerial commitment	productivity benefits	0.289	<0.001	accepted
H5	TPM implementation	productivity benefits	0.289	<0.001	accepted
H6	PM implementation	productivity benefits	0.122	=0.009	accepted

Figure 2 also shows the R^2 values from the dependent latent variables. In SEMs, R^2 expresses the amount of variance in a dependent variable that is explained by one or more independent variables. For instance, the TPM implementation latent variable shows R^2 = 0.628, which is explained by managerial commitment (0.400) and PM implementation (0.228). In turn, PM implementation is explained by only one latent variable, managerial commitment, with R^2 = 0.407.

Finally, the productivity benefits latent variable is explained in 0.382 units by three latent variables: managerial commitment (0.162), PM implementation (0.057), and TPM implementation (0.164). These results imply that to ensure proper TPM implementation, it is important to perform tasks from managerial commitment, since this latent variable explains 40% of the PM implementation. Similarly, to obtain productivity benefits, companies must have managerial commitment and TPM implementation, because those variables have a higher explanatory level.

5.3.2. Indirect Effects

Figure 2 displays four indirect effects, the *p*-value for its statistical validation, and the size effect (SE) as an explanatory power: three of them occur through two segments, and one occurs through three segments. Similarly, Table 7 lists the sum of indirect effects and associates them with their corresponding *p*-values and SEs. For instance, managerial commitment is indirectly related to TPM implementation through PM implementation. This indirect relationship is statistically significant ($p < 0.001$) and has a value of 0.214, explaining 16.0% of variability.

Table 7. Indirect effects.

Dependent Variable	Independent Variable	
	Managerial Commitment	**PM Implementation**
TPM implementation	0.214 $p < 0.001$ ES = 0.160	-
productivity benefits	0.293 $p < 0.001$ ES = 0.165	0.097 $p = 0.004$ ES = 0.045

Likewise, the managerial commitment latent variable has an indirect effect on productivity benefits through two latent variables, TPM implementation and PM implementation; the value of this indirect effect is 0.293 and it can explain 16.5% of variability. Finally, PM implementation has an indirect effect on productivity benefits through TPM implementation with a low value of 0.097, but it is still statistically significant and can explain 4.5% of variability.

5.3.3. Total Effects

Total effects in a relationship are total direct and indirect effects. In this sense, Table 8 shows the total effects found in the model, the *p*-value associated with the statistical test, and the size effect. For instance, the total effects in the relationship between managerial commitment and productivity benefits (0.582) consists of the total direct effect (0.289) and the indirect effect (0.232).

5.3.4. Sensitivity Analysis

Table 9 presents the probabilities of occurrence independently for the latent variables analyzed by their high and low scenarios. For example, it is observed that the probability that managerial commitment is presented at a low level is only 0.158, which represents a risk for the maintenance manager, since it fully demonstrates that TPM implementation can only be possible if there is precedence for it. Similarly, the probability of having managerial commitment in a high scenario is 0.190. Interpretations of the other latent variables are performed in a similar way; in this case, the low levels represent a risk or an improvement opportunity for maintenance managers to avoid this occurrence.

Table 8. Total effects.

Dependent Variable	Independent Variable		
	Managerial Commitment	**TPM Implementation**	**PM Implementation**
TPM implementation	0.748 $p < 0.001$ ES = 0.561	-	0.335 $p < 0.001$ ES = 0.228
PM implementation	0.638 $p < 0.001$ ES = 0.407	-	-
productivity benefits	0.582 $p < 0.001$ ES = 0.326	0.289 $p < 0.001$ ES = 0.164	0.218 $p < 0.001$ ES = 0.102

Table 9. Scenarios and probabilities of independent occurrence.

Latent Variable	Scenario	Probability
managerial commitment	−	0.158
	+	0.190
TPM implementation	−	0.160
	+	0.166
PM implementation	−	0.190
	+	0.179
productivity benefits	−	0.155
	+	0.190

According to the previous information and based on the values of the variables in their low scenarios, one of the biggest risks is to have a failure in the PM implementation process, since there is a probability of 0.190. Consequently, managers must work hard to generate a work culture focused on preservation of production equipment, because according to the model presented in Figure 1, the success of a more complete program depends on it, as the TPM implementation. Likewise, it is observed that two latent variables have a high probability of occurrence in their high scenarios, managerial commitment and productivity benefits, with 0.190, therefore managers must focus their efforts on increasing those values.

Table 10 shows the high and low scenario combinations for the variables analyzed, where the dependent variables are presented in rows and the independent variables in columns, although each value in every relationship can be discussed. In this section, some of them are analyzed in an illustrative way. In addition, for each of the intersections, the probability of occurring simultaneously for the two variables is represented by "&" and the conditional probability of occurrence of a dependent variable because the independent variable has occurred is represented by "If." Thus, there are scenarios that are pessimistic where the two levels of the variables are low, and there are scenarios that are optimistic because the two variables are at their high level.

Table 10. Scenarios and probabilities for independent occurrence.

Dependent Variable	Scenario	Independent Variable: Managerial Commitment −	Managerial Commitment +	TPM Implementation −	TPM Implementation +	PM Implementation −	PM Implementation +
TPM implementation	−	& = 0.098 If = 0.621	& = 0.003 If = 0.016				
	+	& = 0.005 If = 0.034	& = 0.095 If = 0.565				
PM implementation	−	& = 0.090 If = 0.569	& = 0.008 If = 0.048	& = 0.092 If = 0.486	& = 0.003 If = 0.014		
	+	& = 0.008 If = 0.052	& = 0.084 If = 0.500	& = 0.005 If = 0.030	& = 0.087 If = 0.485		
productivity benefits	−	& = 0.065 If = 0.414	& = 0.00 If = 0.00	& = 0.076 If = 0.475	& = 0.003 If = 0.016	& = 0.065 If = 0.343	& = 0.003 If = 0.015
	+	& = 0.027 If = 0.172	& = 0.068 If = 0.403	& = 0.027 If = 0.169	& = 0.065 If = 0.393	& = 0.024 If = 0.129	& = 0.063 If = 0.348

For instance, a pessimistic scenario can occur when managerial commitment and PM implementation have simultaneously low levels, which has a simultaneous probability of 0.090, representing a risk for the maintenance manager. However, the probability of the second latent variable occurring since the first variable has happened is 0.569; in other words, if there is a low managerial commitment to implementation of the maintenance program, the probability is 0.569 that the policies focused on machinery and equipment preservation are also at their low level. In order to avoid these scenarios during the TPM implementation process, it is important to have managerial commitment at its high level, since the probability that this scenario is presented along with a low level in PM implementation is only 0.008, which indicates that it will almost never happen, which shows the importance of that variable. Also, the probability of having a low level in PM implementation because there is a high managerial commitment level is 0.048, a very low value that indicates that the second variable in high levels is not associated with low levels in first variable.

The above statement is easily demonstrated when the scenario is analyzed with the variables inverted, that is, when managerial commitment is low and PM implementation is high, which can occur simultaneously at a probability of 0.008, and this indicates that it will almost never happen. Also, it is observed that it is very unlikely that the second variable will occur in its scenario because the first variable has happened, since the probability is only 0.052. However, when managerial commitment and PM implementation have high levels simultaneously, there is a probability of occurrence of 0.084, but the probability that the second variable occurs at its high level since the first variable occurred at its high level is 0.500. The previous data clearly indicate that high managerial commitment levels are related to high PM implementation levels.

How does TPM implementation impact productivity benefits? In order to answer this question, the situation where the first variable is independent and the second is dependent is analyzed. In this case, in the pessimistic environment, when the two variables are at their low level, it is observed that there is a probability of 0.076 that this scenario will occur. However, the probability of having low productivity benefits because the TPM implementation at its low level is 0.475, which indicates that the low levels of the second variable are related to the low levels of the first. Additionally, in an optimistic environment, when TPM implementation and productivity benefits have high levels, the probability that they will occur simultaneously is 0.065, which represents a low value for a maintenance manager; however, the probability that the second variable will occur because the second variable has occurred in its scenario is 0.393. The previous data indicate that TPM implementation is a program that guarantees productivity benefits.

In addition, the previous statement is easily validated when the probability of TPM implementation is at a high level and productivity benefits is at a low level, which has a value of 0.003, indicating that this scenario will almost never occur. Also, the probability that the second variable is at its low level because the first variable is at its high level is only 0.016, which indicates that TPM implementation at a high level is not associated with productivity benefits at a low level. Due to space problems, the interpretation of other scenarios between the latent variables is left to the reader, with an explanation similar to the one that is presented.

A structural equation model was executed, integrating data from the automotive sector, with 172 cases, and another model integrates 159 cases from the aeronautics, electric, electronics, medical, and other sectors. Table 11 shows the β values for every model in the multigroup analysis, for example, for the relationship between managerial commitment and PM implementation for the automotive model it is 0.654 and for the same relationship in the other sectors model it is 0.631, a similar value that needs to be tested statistically for its difference.

Table 11. Beta values for models.

Dependent Variable	Automotive Sector			Other Sectors		
	Independent Variable					
	MC	PMI	TPMI	MC	PMI	TPMI
PM implementation	0.654	-	-	0.631	-	-
TPM implementation	0.49	0.364	-	0.573	0.298	-
productivity benefits	0.277	0.233	0.436	0.304	0.210	0.359

MC, managerial commitment; PMI, PM implementation; TPMI, TPM implementation.

Table 12 shows the confidence intervals for differences between two β values in the analyzed models (automotive sector and other sectors) at a 95% confidence level. For every β value, it is observed that the lower confidence value limit is negative and the upper confidence value limit is positive, and this lets us conclude that there are no differences between analyzed groups, because the zero value is included in that interval.

Table 12. Confidence intervals for differences in β.

Dependent Variable	Independent Variable		
	Managerial Commitment	TPM Implementation	PM Implementation
TPM implementation	–0.098 to 0.1333	-	-
PM implementation	–0.069 to 0.141	–0.096 to 0.115	-
productivity benefits	–0.032 to 0.178	–0.035 to 0.174	–0.104 to 0.107

6. Conclusions and Industrial Implications

Based on the findings previously discussed, the research conclusions are as follows:

1. Based on the R^2 values, TPM implementation has a 62.8% dependence on two variables, but managerial commitment explains most of the variability in 40%. In this sense, manufacturing companies must encourage department leaders and managers to embrace their responsibility for and commitment to TPM. Similarly, managers must promote the active participation of maintenance staff and communicate a corporate vision centered on quality and equipment maintenance, and among these aspects, they must be actively involved in TPM projects. Two other responsibilities of senior managers are to make sure that staff commitment to TPM is aligned with the corporate mission and supervise tracking of the implemented maintenance plans.

2. The managerial commitment latent variable explains 40.7% of PM implementation variability. Therefore, for a preventive maintenance program to be successful, managerial commitment is necessary. Hence, PM programs must be focused on adjusting and changing components before the equipment fails. Also, preventing machine failures must be promoted by managers, since they need to understand the components' life cycle and generate a replacement plan.
3. TPM is a set of programs, among which is preventive maintenance. According to the findings, PM implementation is an important antecedent to any comprehensive TPM program. In fact, in this research, PM implementation explains 22.8% of the variability of TPM implementation. These findings imply that TPM managers and operators must focus their efforts on preventive maintenance programs that consider the components' life cycle to make changes before machines fail.
4. Statistically, three latent variables explain 38.3% of the productivity benefits latent variable: TPM implementation (16.4%), managerial commitment (16.2%), and PM implementation (5.7%). Such estimates imply that managers must pay close attention to the first two variables, since they have the largest effects. Although the direct impact from PM implementation is low in productivity benefits, the indirect effect has a value of 0.097, which can explain 4.55%. In the end, the total effects of PM implementation on productivity benefits have a value of 0.218 units, and this latent variable explains up to 10.2%. In other words, preventive maintenance as a part of TPM implementation is vital if companies aim to obtain productivity benefits.
5. The total effects of managerial commitment are larger than 0.5 standard deviations, demonstrating that this variable is a key element in productivity, TPM success, and PM programs. Consequently, TPM operators must always demand managerial support before starting any preventive maintenance program, because managerial commitment on its own does not guarantee all the productivity benefits, since its direct effects on this variable were only 0.289. On the other hand, the total effects of managerial commitment on productivity benefits where the TPM and PM were involved had a value of 0.582.
6. It is interesting to observe the relationship between managerial commitment and productivity benefits obtained from TPM, where the direct effect was only 0.289, but the indirect effect that occurs through the mediating variables PM implementation and TPM implementation was 0.293, that is, the indirect effect is greater than the direct effect, and the sum gives a total effect of 0.582. The foregoing indicates that management commitment is not sufficient to obtain productivity benefits, because it is necessary to have a labor culture focused on conserving the machinery and equipment that can be reflected in a preventive maintenance program, but in addition, a more holistic TPM implementation program in which all departments of the company are integrated is required.
7. Based on information in Table 10, the following conclusions can be summarized:

    a. High managerial commitment levels are not associated with low productivity benefits levels, even if the probability of simultaneous occurrence is zero.
    b. Even if managerial commitment is low, it is possible to obtain high productivity benefits, because these may come from other sources.
    c. Having low managerial commitment levels represent a risk in PM implementation, TPM implementation, and productivity benefits.
    d. High TPM implementation levels guarantee high productivity benefits levels.

8. There is no statistical evidence to declare that the automotive industrial sector is different from other sectors when multiple groups are analyzed.

7. Research Limitations and Suggestions for Future Work

TPM offers a broad range of benefits for companies, yet this research only analyzes the impact of TPM on productivity. This is one of the limitations in the study, and in order to address it, further research would have to expand the scope by considering other benefits, such as employee safety benefits and organizational benefits. Another limitation in the proposed model and its hypotheses is that it was evaluated using information from the Mexican maquiladora industry, and the same model using data from other geographical areas and industrial sectors may have different results.

Similarly, a successful TPM implementation is not the result of just managerial commitment and PM programs; it is important to explore the impact of other critical success factors, such as machinery technology, employee commitment, employee education and training, tool maintenance, and equipment, and as a result, R-squared is not equal to 1, because another latent variable is not integrated into the model.

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