TESIS DE LA UNIVERSIDAD
DE ZARAGOZA

2022

181

Francisco Gil Vilda

Diseño Desde la Persona: hacia una metodología de diseño de Sistemas de Producción Lean basada en el respeto a las personas y la optimización de la superficie

Person-Based-Design: towards a design methodology for Lean Production Systems based on respect-for-human and surface optimization

Director/es

Yagüe Fabra, José Antonio
Sunyer Torrents, Albert

ISSN 2254-7606

Prensas de la Universidad
Universidad Zaragoza

ISSN 2254-7606

Tesis Doctoral

DISEÑO DESDE LA PERSONA: HACIA UNA METODOLOGÍA DE DISEÑO DE SISTEMAS DE PRODUCCIÓN LEAN BASADA EN EL RESPETO A LAS PERSONAS Y LA OPTIMIZACIÓN DE LA SUPERFICIE

PERSON-BASED-DESIGN: TOWARDS A DESIGN METHODOLOGY FOR LEAN PRODUCTION SYSTEMS BASED ON RESPECT-FOR-HUMAN AND SURFACE OPTIMIZATION

Autor

Francisco Gil Vilda

Director/es

Yagüe Fabra, José Antonio
Sunyer Torrents, Albert

UNIVERSIDAD DE ZARAGOZA
Escuela de Doctorado

Programa de Doctorado en Ingeniería de Diseño y Fabricación

2022

Universidad Zaragoza
1542

TESIS DOCTORAL

Diseño Desde la Persona: hacia una metodología de diseño de Sistemas de Producción Lean basada en el respeto a las personas y la optimización de la superficie.

Person-Based-Design: towards a design methodology for Lean Production Systems based on respect-for-human and surface optimization.

Francisco Gil Vilda

Zaragoza, 2022

Diseño Desde la Persona: hacia una metodología de diseño de Sistemas de Producción Lean basada en el respeto a las personas y la optimización de la superficie.

Person-Based-Design: towards a design methodology for Lean Production Systems based on respect-for-human and surface optimization.

Francisco Gil Vilda

Dirigida por:

Dr. José Antonio Yagüe Fabra

Dr. Albert Sunyer Torrents

Para la obtención del Título de
Doctor por la Universidad de Zaragoza.

Zaragoza, Julio de 2022

Esta tesis doctoral se presenta como compendio de las siguientes publicaciones:

- Gil-Vilda, F., Sune, A., Yagüe-Fabra, J. A., Crespo, C., & Serrano, H. (2017). Integration of a collaborative robot in a U-shaped production line: a real case study. Procedia Manufacturing, 13. https://doi.org/10.1016/j.promfg.2017.09.015.

- Gil Vilda, F., Yagüe-Fabra, J. A., Sune Torrents, A., Jauregui-Becker, J. M., & Wits, W. W. (2018). A geometrical model for managing surface productivity of U-shaped assembly lines. CIRP Annals, 67(1). https://doi.org/10.1016/j.cirp.2018.04.047.

- Gil Vilda, F., Yagüe Fabra, J. A., & Sunyer Torrents, A. (2019). Person-based design: A human-centered approach for lean factory design. Procedia Manufacturing, 41. https://doi.org/10.1016/j.promfg.2019.09.031.

- Gil Vilda, F., Yagüe-Fabra, J. A., & Sunyer Torrents, A. (2020). An in-plant milk-run design method for improving surface occupation and optimizing mizusumashi work time. CIRP Annals, 69(1). https://doi.org/10.1016/j.cirp.2020.03.012.

- Gil-Vilda, F., Yagüe-Fabra, J. A., & Sunyer, A. (2021). From lean production to lean 4.0: A systematic literature review with a historical perspective. In Applied Sciences (Switzerland) (Vol. 11, Issue 21). https://doi.org/10.3390/app112110318.

Departamento de
Ingeniería de
Diseño y Fabricación
Universidad Zaragoza

D. **José Antonio Yagüe Fabra**, Doctor por la Universidad de Zaragoza y Profesor Titular del departamento de Ingeniería de Diseño y Fabricación de la Universidad de Zaragoza.

INFORMA:

Que la tesis titulada "Diseño Desde la Persona: hacia una metodología de diseño de Sistemas de Producción Lean basada en el respeto a las personas y la optimización de la superficie.", elaborada por D. Francisco Gil Vilda, ha sido realizada bajo mi dirección, se ajusta al proyecto de tesis inicialmente presentado y cumple los requisitos exigidos por la legislación vigente para optar al grado de Doctor por la Universidad de Zaragoza. Una vez finalizada, autorizo su presentación en la modalidad de compendio de publicaciones para ser evaluada por el tribunal correspondiente.

Zaragoza, a 23 de mayo del 2022

Fdo. D. José Antonio Yagüe Fabra

D. **Albert Sunyer Torrents**, Doctor por la Universidad Politécnica de Cataluña (UPC) y Profesor Agregado del Departamento de Organización de Empresas.

INFORMA:

Que la tesis titulada "Diseño Desde la Persona: hacia una metodología de diseño de Sistemas de Producción Lean basada en el respeto a las personas y la optimización de la superficie.", elaborada por D. Francisco Gil Vilda, ha sido realizada bajo mi dirección, se ajusta al proyecto de tesis inicialmente presentado y cumple los requisitos exigidos por la legislación vigente para optar al grado de Doctor por la Universidad de Zaragoza. Una vez finalizada, autorizo su presentación en la modalidad de compendio de publicaciones para ser evaluada por el tribunal correspondiente.

Barcelona, a 23 de mayo del 2022.

Fdo. Dr. Albert Sunyer Torrents

A mi familia.

AGRADECIMIENTOS

Esta tesis doctoral es el fruto de seis años de trabajo apasionante en un campo al que he dedicado mi trayectoria profesional. Un camino con buenos momentos, momentos de desánimo y un balance muy positivo de aprendizaje y diversión. Un resultado que no habría sido posible sin las personas a las que debo un agradecimiento profundo:

En primer lugar, a mis directores de tesis: a José Antonio por animarme a dar el paso y orientarme en la difícil misión de publicar; a Albert por sus sabios consejos en la búsqueda bibliográfica y su visión pragmática; a ambos por darme ánimos en los momentos más difíciles.

En segundo lugar, a François Ledoux, mi "Sensei" en Valeo porque me regaló generosamente su sabiduría y me acompañó en los siempre difíciles inicios profesionales. Le debo las bases del conocimiento del que aún me alimento (en el sentido académico y material).

En tercer lugar, a mis padres que en paz descansen. A mi madre por su empeño en dejarme como herencia la mejor forma de ganarme la vida: una cabeza bien cultivada. A mi padre por su compañía silenciosa pero siempre disponible.

En cuarto lugar, a mis hijas Sara y Marta por darme la alegría de vivir y aguantarme los rollos con paciencia y, en general, un interés bien disimulado.

Por último, dado que los últimos en realidad son los primeros, a mi mujer Elena. Por su presencia en los momentos más difíciles; por su amor generoso hasta lo incomprensible que me ha ayudado a desarrollarme como la persona que soy.

Contenidos

Lista de Figuras

Lista de Tablas

Lista de Abreviaturas

CoBot	Collaborative Robot	Robot Colaborativo
D	Customer demand	Demanda del cliente
IMVP	International Motor Vehicule Program	Programa Internacional de Vehículos a Motor
JCR	Journal Citation Reports	
JIT	Just In Time	Justo A Tiempo
LPS	Lean Production System	Sistema de Producción Lean
MIT	Massachusetts Institute of Technology	Instituto Tecnológico de Massachusetts
POU	Point Of Use	Punto de consumo
QCC	Quality Control Circles	Círculos de Calidad
SJR	Scimago Journal Rank	
SLR	Systematic Litereture Review	Revisión Sistemática de la Literatura
Tma	Manual Assembly Time	Tiempo de ensamblaje manual
TPS	Toyota Production System	Sistema de Producción Toyota
TQC	Total Quality Control	Control de Calidad Total
TQM	Total Quality Management	Gestión de la Calidad Total
TT	Takt Time	Ritmo del cliente
U-SAL	U-Shaped Assembly Line	Célula en U

Resumen

En las últimas décadas, el incremento de la competitividad de los mercados globales ha popularizado en término "Lean" como una forma de organización industrial capaz de conseguir altos niveles de calidad, productividad y cortos plazos de entrega, en un entorno de producción de series cortas y variadas. Hasta el punto de que su sobreuso ha generado confusión y una cierta pérdida de su sentido original.

Los Sistemas de Producción Lean se basan en el Sistema de Producción Toyota, desarrollado en los años 60 del siglo XX y ampliamente difundido a partir de los años 90 como "*Lean Production*" tras las conclusiones del *International Motor Vehicule Program* (IMVP) conducido por el *Massachusetts Institute of Technology* (MIT) desde 1979.

Uno de los pilares fundacionales del Sistema de Producción Lean es el respeto por las personas (*respect-for-human*). Sin embargo, la literatura muestra una falta de interés sobre este concepto, a la vez que una progresiva pérdida de visión holística en favor de las herramientas.

En este sentido, el análisis de la bibliografía sobre la aplicación de dichas herramientas muestra una paradoja difícil de conciliar: ¿cómo se puede implicar a las personas en la mejora de la eficiencia del sistema si ello puede acarrear su despido?

El objeto de esta tesis es proponer una metodología de diseño para un Sistema de Producción Lean que ayude a mitigar esta paradoja y se apoye, como indicador de mejora, en la productividad de la superficie en lugar de la tradicional productividad humana.

Para ello propone el método *Person-Based Design* (Diseño desde la Persona) en siete capas concéntricas con una única regla de diseño: mejorar la eficiencia de cada capa sin que ello perjudique la eficiencia de las capas que contiene.

Después desarrolla metodologías concretas de diseño y optimización de las 5 capas más internas con la reducción del espacio industrial ocupado como hilo conductor. En particular, modeliza una topología de Células en U orientada a la gestión óptima del espacio ocupado; después propone un método de diseño de su sistema de aprovisionamiento (*milk-run*) para minimizar la superficie y el esfuerzo del conductor; finalmente muestra cómo la introducción de tecnologías de la Industria 4.0 puede contribuir a compactar células de producción eliminado trabajos penosos para las personas a través del uso de robots colaborativos (*Cobots*).

Abstract (English)

In recent decades, the increasing competitiveness of global markets has popularized the term "Lean" as a method of industrial organization able to achieve high levels of quality, productivity, and short delivery times, in an environment of small batches production. Its overuse has generated confusion and a certain loss of its original meaning.

Lean Production Systems are based on the Toyota Production System, developed in the 60s of the 20th century and widely disseminated in the 90s as "*Lean Production*" after the conclusions of the *International Motor Vehicle Program* (IMVP) conducted by the *Massachusetts Institute of Technology* (MIT) since 1979.

One of the foundational pillars of the Lean Production System is *respect-for-human*. However, the literature shows a lack of interest in this concept, as well as a progressive loss of holistic vision in favor of its tools.

In this sense, the analysis of the literature shows a paradox difficult to conciliate: how can people be involved in improving the efficiency of the system if this they can lost their jobs?

The purpose of this thesis is to propose a design methodology for a Lean Production System that helps to mitigate this paradox using as metric the surface productivity instead of the traditional labor productivity.

To do this, this research proposes the *Person-Based Design* method developed in seven concentric layers with a single design rule: improve the efficiency of each layer without harming the efficiency of the layers that it contains.

Then, it develops concrete methodologies of design and optimization of the five innermost layers with the reduction of industrial space as a common goal. In particular, the method models a U-shaped cell topology oriented to the optimal management of the space; then it proposes a design method for its internal supply system (*milk-run*) to minimize the surface and the driver workload; finally, it shows how the introduction of Industry 4.0 technologies can contribute to compacting production cells eliminating painful work for people through the use of collaborative robots (*Cobots*).

1. Introducción

En las cuatro últimas décadas, el entorno organizativo de las empresas se ha visto sometido a profundos cambios debidos a la progresiva globalización de la economía, la predominancia de criterios financieros de gestión y las crecientes exigencias de los mercados globales de clientes y consumidores.

Estos cambios han sumido al mundo industrial en mercados altamente competitivos, con ciclos de vida de los productos cada vez más cortos, demandas de productos cada vez más personalizados, altas exigencias de calidad, presión a la baja en los precios y necesidad de plazos de entrega cada vez más cortos (Jasti & Kodali, 2015).

Estas demandas han enfrentado a la industria manufacturera a crecientes desafíos en varios ámbitos:

- Gestionar un aumento de la complejidad del producto provocada por la multiplicación de referencias tanto de productos acabados como de materias primas y componentes.
- Asegurar niveles de calidad cada vez más elevados.
- Atender a demandas cada vez más fraccionadas que necesitan una producción en series cortas y variadas, lo que exige mejoras drásticas de la flexibilidad de las instalaciones.
- Reducir costes, lo que pone una elevada presión en la productividad, mayoritariamente focalizada en la reducción y/o abaratamiento de la mano de obra.
- Conseguir plazos de entrega muy cortos, pero con mínimos niveles de stock, lo que exige continuos esfuerzos por reducir el *Lead Time* del sistema de producción.

Estos desafíos han sido respondidos por la industria con diferentes estrategias que mayoritariamente han pasado por la deslocalización a áreas geográficas de bajos costes de mano de obra, el aumento de la automatización y la implantación de sistemas de producción mejor adaptados a las nuevas exigencias.

Los últimos acontecimientos a nivel mundial (pandemia COVID-19, cambios geopolíticos) han mostrado las flaquezas de algunas de estas estrategias como la deslocalización de productos estratégicos. Este hecho está provocando una incipiente tendencia a reintegrar la producción a países con mayor coste de mano de obra, personas más formadas y cualificadas y, por tanto, con mayores expectativas sobre su desarrollo profesional y humano (Pujawan & Bah, 2022).

Por otra parte, la automatización indiscriminada también ha mostrado sus limitaciones debido, mayoritariamente, a sus costes de puesta en marcha, el aumento de la complejidad (que requiere personal muy cualificado para su gestión) y la inflexibilidad que introduce en los procesos, limitando la producción en series cortas y variadas (Coffey & Thornley, 2006; Gorlach & Wessel, 2008).

Si bien el desafío de producir en zonas geográficas desarrolladas (con elevado coste de mano de obra y mayores expectativas de bienestar de las personas) nunca ha desaparecido del todo, es posible que sea creciente en un futuro próximo (Wang & Sun, 2021).

Ante esta tesitura, en el campo de las operaciones industriales, "Lean" se ha extendido como un sistema de gestión capaz de alcanzar los objetivos de alta calidad, bajos costes y plazos cortos simultáneamente (Antony et al., 2020; Moyano-Fuentes & Sacristán-Díaz, 2012; Psomas & Antony, 2019).

Esta tendencia es comprensible dado que los Sistemas de Producción Lean se inspiran en el Sistema de Producción Toyota (TPS) que fue desarrollado entre los años 50 y 70 del sigo XX para enfrentarse a unas condiciones económicas en Japón que, tras las Segunda Guerra Mundial, se asemejaban a las descritas para la actualidad en los países desarrollados (Ohno, 1982, pp. 1–2):

- Bajas tasas de crecimiento con una demanda estancada.
- Elevada competencia con presión a la baja de los precios que exigen altas mejoras de productividad para reducir costes.
- Diversificación de productos como forma de competir lo que exige una producción en series cortas y muy variadas.
- Entorno social con una mano de obra cara y cualificada.

El propio Taiichi Ohno, reconocido unánimemente (Hall, 1983; Monden, 1983; Sugimori et al., 1977; Womack et al., 1990) como el creador e impulsor del *Toyota Production System*, lo relata en su libro seminal y define el TPS como "*a multi-kind, small-quantity production system*" (sistema de producción multi-producto en pequeñas cantidades) (Taiichi Ohno, 1988, p. XIV) basado en "*the absolute elimination of waste*" (la absoluta eliminación del derroche) (Taiichi Ohno, 1988, p. 4).

Por lo tanto, se daban entonces unas características de la situación económica muy parecidas a las actuales que mantienen plenamente vigente la adopción de Sistemas de Producción Lean en el mundo industrial.

El TPS se dio a conocer en occidente en los años 80 del siglo XX a través de investigadores japoneses (Monden, 1983; Shingo, 1981), estadounidenses (Hall, 1983; Schonberger, 1982) y europeos (Bounine & Suzaki, 1986).

A partir de la década de los 90 se expandió adoptando definitivamente el sobrenombre "*Lean Production*" o "*Lean Manufacturing*" a raíz del éxito del *bestseller "The machine that changed the world"* (La máquina que cambió el mundo) (Womack et al., 1990), libro basado en las investigaciones del IMVP conducido por el MIT a partir de 1979.

A inicios del siglo XXI el concepto "Lean" se diversificó y aplicó a diferentes ámbitos empresariales generando un elevado interés académico e industrial. Su sobreuso y en ocasiones su aplicación sesgada o incompleta crearon también confusión y una cierta pérdida de sentido (Schonberger, 2019; Shah & Ward, 2007).

La adopción de los Sistemas de Producción Lean nunca ha sido capaz de resolver una paradoja relacionada con la integración de las personas en el sistema. Esta paradoja fue descrita por primera vez en 1983 por R. W. Hall (1983, p. 270), uno de los primeros investigadores norteamericanos del TPS.

En el contexto de esta tesis dicha paradoja puede describirse así:

"Lean" ha sido profusamente difundido como un sistema de gestión que permite la mejora de la competitividad (Antony et al., 2020; Moyano-Fuentes &

Sacristán-Díaz, 2012). Desde su origen la involucración de las personas se ha considerado como una condición necesaria para el éxito del sistema (Antony et al., 2020; Hall 1983; Liker, 2004; Monden, 1983; Shimada & MacDuffie, 1986). Sin embargo, una aplicación muy sesgada hacia el aumento de la productividad humana en las fábricas (Rehder, 1992) deriva a menudo en una fuerte presión sobre las personas, un entorno de trabajo incómodo y estresante (Conti et al., 2006) y, en el límite, la extinción de puestos de trabajo (Gil Vilda et al., 2019). Es una paradoja pedir a las personas que se involucren en un proceso que les puede hacer perder su empleo, tal y como fue muy bien descrito por Hasle et al. (2012, p. 830):

"*The lean focus on the reduction of waste implied that employees could be made redundant, and it could not be expected than employees would be motivated in such process.*"

(El foco del Lean en la reducción del derroche implica que los empleados pueden ser despedidos y no se puede esperar que los empleados encuentren motivación en semejante proceso).

1.1. Motivación

La motivación de esta Tesis Doctoral parte de la praxis directa del autor en empresas industriales manufactureras, tras más de 25 años poniendo en marcha, practicando y observando alrededor de los Sistemas de Producción Lean, desde que a mediados de los años 90 el Sistema de Producción Toyota empezó a introducirse en Europa.

La práctica y observación de los Sistemas de Producción Lean ha supuesto indefectiblemente encontrarse con la paradoja, descrita en el apartado anterior, que implica abordar la pregunta: ¿Cómo integrar a las personas en el Sistema sin que vean amenazado su puesto de trabajo?

Adicionalmente, a través de la práctica profesional, el autor ha observado la evolución del “Lean” y sus diferentes periodos de difusión: su descubrimiento en Occidente, el entusiasmo inicial, su caída en el olvido, su extensión a otros ámbitos, su sofisticación y su nueva popularización. Como todo lo que se populariza y extiende fuera de su ámbito original, el abuso del término Lean ha creado confusión y una pérdida de su significado hasta ponerlo en riesgo de convertirlo en una *pragmatic ambiguity* (ambigüedad pragmática) como la define Giroux (2006) y Dorval et al. (2019) la aplican para el término *Lean Culture*. O incluso peor, como Schonberger recientemente avisa, en riego de desintegración y total perdida de sentido (Schonberger, 2019).

En este ámbito, la motivación de esta Tesis se centra en dos aspectos:

- Investigar los orígenes, evolución histórica y diversificación del Lean como sistema de organización hasta nuestros días, con el objeto de identificar brechas conceptuales y metodológicas. En este sentido cada uno de los artículos que componen esta tesis incluye una revisión de la bibliografía con este enfoque de análisis histórico. Adicionalmente, uno de los artículos constituye una extensa revisión de la literatura con un enfoque histórico.
- Proponer una metodología basada en fundamentos sólidos para el diseño de Sistemas de Producción Lean que, si no resuelvan, al menos mitiguen la

paradoja expuesta; así como encontrar una forma de medición de la mejora del sistema de producción en consonancia con el respeto a las personas.

El proceso de elaboración de la tesis se ha basado mayoritariamente en datos empíricos recopilados sobre el terreno por el autor. La compilación, estructuración, análisis y síntesis de estos datos ha dado lugar a propuestas metodológicas que posteriormente se han validado empíricamente. Así pues, esta tesis ha utilizado una metodología mayoritariamente inductiva.

1.2. Estado del arte.

La revisión de la literatura muestra un amplio acuerdo (Ciano et al., 2019; Holweg, 2007; Jasti & Kodali, 2015; Moyano-Fuentes & Sacristán-Díaz, 2012; New, 2007; Shah & Ward, 2007; Womack et al., 1990) acerca de que el término "Sistema de Producción Lean" (*Lean Production System*) fue acuñado en 1988 por John F. Krafcik en su trabajo académico *Triumph of the Lean Production System* (Krafcik, 1988) en el seno del IMVP, desarrollado por el MIT y patrocinado por varios fabricantes de automóviles estadounidenses y europeos, en parte motivado por la crisis del petróleo del año 1973 (Holweg, 2007).

El claro objetivo de este programa, como el propio Krafcik describe, era "*to assess the range of manufacturing performance, particularly productivity performance, around the World*" (evaluar el rango del rendimiento de la producción manufacturera, en particular su productividad, alrededor del mundo). Los resultados mostraban una clara supremacía de Toyota - que no patrocinaba el programa - frente a otros fabricantes occidentales. De esta forma, como sugiere New (2007, p. 3547), parece que *Lean Production System* fue escogido como *"an acceptable way of describing TPS without offending the other sponsors of the IMVP research"* (un modo aceptable de describir el Sistema de Producción Toyota sin nombrar a Toyota para no ofender a los otros patrocinadores del IMVP).

Para encontrar, por lo tanto, los orígenes de los Sistemas de Producción Lean, debemos remontarnos a la génesis del TPS.

Hay un consenso general en la literatura (Bhamu & Sangwan, 2014; Dorval et al., 2019; Holweg, 2007; New, 2007; Shah & Ward, 2007) acerca de que el primer artículo escrito en inglés que introduce el término *Toyota Production System* fue presentado en la *4th International Conference of Production Research* en Tokyo en 1977 bajo el título *Toyota production system and Kanban system. Materialization of just-in-time and respect-for-human system* (Sugimori et al., 1977).

Los autores se declaran discípulos de Taiichi Ohno, al que reconocen como creador y promotor del TPS y describen el sistema fundamentado sobre los dos pilares indisociables:

- *Just-In-Time production*. Que puede ser identificada como la parte técnica del sistema. Las herramientas "*hard*" como se describen en la literatura (Danese et al., 2018).
- *Respect-for-human*. Relacionado con tratar a los trabajadores como seres humanos con consideración y permitiendo el completo desarrollo de sus capacidades. Corresponde con las prácticas "*soft*" (Danese et al., 2018).

En particular, el pilar *respect-for-human* se presenta cimentado sobre tres bases conceptuales:

- Foco en utilizar el esfuerzo humano en tareas útiles, evitando operaciones de derroche.
- Garantizar la seguridad de la persona, evitando tareas que la puedan dañar.
- Desarrollar las capacidades de las personas a través de la participación, la responsabilidad y el empoderamiento.

Es este pilar el que esta tesis recupera en su título como "respeto por las personas".

Para entender la génesis del *respect-for-human* dentro del TPS, es necesario retrotraerse a los años 50 de la historia industrial japonesa (Cusumano, 1985; Sato & Hoshino. 1984), cuando confluyeron tres factores clave:

- Después de la Segunda Guerra Mundial Japón tuvo que reconstruir completamente su economía. Esta necesidad está muy bien descrita por Ohno cuando relata que K. Toyoda (presidente de Toyota Motor) le desafió en 1945 a "*Catch up with America in three years*" (alcanzar a América en tres años) (Ohno, 1982).
- Los gurús norteamericanos Edward Deming y Joseph Juran enseñaron en Japón durante los años 50 y sus ideas promovieron un nuevo enfoque para los Sistemas de Producción en las firmas japonesas, bajo el concepto "*Total Quality Control*" (TQC) y su evolución posterior a "*Total Quality Management*" (TQM) (Taylor, 1994).

- Al mismo tiempo, el sistema de "empleo para toda la vida" fue adoptado en Japón, favoreciendo un sentimiento de pertenencia a la organización por parte de managers y trabajadores (Sato & Hoshino, 1 984, p. 5).

Estos tres factores crearon los cimientos para unas relaciones laborales basadas en la confianza y la participación, que promovió la creación de Círculos de Calidad (QCC) durante los años 60 y 70 en muchas compañías japonesas. Un QCC era un equipo de 5 a 10 trabajadores voluntarios que, fuera del tiempo regular de trabajo, mejoraban su propio trabajo y el entorno productivo (Monden, 1983, p. 11; Sato & Hoshino, 1984, p. 226).

Dentro del propio IMVP, (Shimada & MacDuffie, 1986) se acuñó el término "*Humanware*" para describir la integración de las personas en el sistema. Basado en el análisis de las primeras implantaciones del sistema japonés en EEUU, describe tres aspectos diferenciales: la mejora progresiva de las máquinas a través de las ideas propuestas por los propios trabajadores, la auto-gestión de los equipos de producción y el auto-control de calidad.

Encontramos, por lo tanto, documentado en sus orígenes el indisociable respeto a las personas y su involucración activa, como condición necesaria para el éxito de la implantación del Sistema de Producción Lean. Es por ello sorprendente que la literatura más reciente sobre este tema detecte una brecha de conocimiento al respecto:

Hines et al. (2004) prestan atención a la evolución del Pensamiento Lean (*Lean Thinking*) e identifican la falta de atención a los aspectos humanos como una debilidad para el éxito del Lean y describe las implementaciones realizadas en los años 90 como "focalizadas en herramientas" (Hines et al., 2004, pp. 995–998).

Marodin et al. (2013) identifican seis áreas de investigación, una de ellas la falta de teorías y practicas efectivas para gestionar el lado humano, en contraste con el desarrollado conocimiento sobre herramientas Lean (Marodin & Saurin, 2013, p. 12).

Jasti et al. (2014) revisan las investigaciones empíricas en *Lean Manufacturing* y muestran cómo no prestan mucha atención a los factores humanos (Jasti & Kodali, 2014, pp. 1104, table XXII).

Moyano-Fuentes et al. (2012) analizan la literatura sobre *Lean Production* e identifican la organización del trabajo y el compromiso de los trabajadores como un área para considera en mayor profundidad (Moyano-Fuentes & Sacristán-Díaz, 2012, p. 572).

Danesse et al. (2018) detectan cómo el concepto Lean está cambiando del uso de herramientas hacia un sistema humano-céntrico (Danese et al., 2018, p. 580) e identifican la gestión de los recursos humanos y las innovaciones "*soft*" (desarrollo, liderazgo y otras) como un área para explorar y relacionar con disciplinas como la psicología y la sociología (Danese et al., 2018, p. 596).

Psomas et al. (2019) específicamente detectan "El factor humano involucrado con el Lean como una brecha de investigación en el *Lean Manufacturing*" (Psomas & Antony, 2019, p. 822).

Una de las motivaciones de esta tesis es reducir esta brecha de conocimiento, avanzando en metodologías de diseño que concilien el respeto por las personas en un entorno altamente eficiente y competitivo.

Cabe indagar más en el conocimiento disponible sobre, primero, la pérdida de visión holística; segundo, la falta de atención al concepto *respect-for-human*; y tercero, la realidad de la paradoja descrita (no se puede involucrar personas y con ello ponerlas en riesgo de perder su empleo).

Analizando las publicaciones previas a 1988 (año de creación del término Lean) encontramos varios autores influyentes en la difusión del primer conocimiento en occidente sobre el TPS y por tanto influyentes en sus primeras puestas en marcha fuera de Japón.

En el año 1981 se publicó el primer libro en inglés al respecto: S*tudy of 'Toyota, Production System from Industrial Engineering Viewpoint* (Shingo, 1981). Shingo fue un meticuloso ingeniero que describe de forma muy detallada técnicas y herramientas, insistiendo en la necesaria visión sistémica. Sin embargo, sorprendentemente no menciona ni el concepto *respect-for-human* ni cita el artículo de Sugimori et al. (1977). Shingo plasmó su experiencia en libros muy reconocidos, pero no en artículos académicos. En 1985 estableció una estrecha colaboración con la editorial Productivity Press (dirigida por Norman Bodek) que publicó sus libros con gran difusión: SMED en 1985 (Shingo, 1985) y una nueva traducción de su primer libro en 1998 (Shingo, 1898). Encontramos pues un autor muy influyente que puso el foco en herramientas y técnicas, pero no propuso ningún marco para la integración de las personas en el sistema. Quizá un primer indicio de la poca atención posterior a la parte humana.

En 1982, Schonberger (el primer investigador occidental sobre el tema, aún en activo) sí cita a Sugimori et al. (1977) aunque sólo para prestar atención al concepto Just-In-Time y Kanban. Considera, no obstante, la importancia de la parte humana con un enfoque conductista (citando específicamente a B.F. Skinner) (Schonberger, 1982, pp. 27–30).

En 1983, Yashuiro Monden publica *Toyota Production System* (prologado por Ohno) y dedica el capítulo 9 a *respect for humanity* (Monden, 1983, p. 124) -equivalente al *respect-for-human*- exponiendo dos herramientas prácticas para materializar el concepto: los ya mencionado Círculos de Calidad y los Programas de Ideas de Mejora.

También en 1983, R.W. Hall publica *Zero Inventories* destacando con claridad la importancia de parte humana "*any system is at bottom a human system*" (cualquier sistema es, en la base, un sistema humano) (Hall, 1983, p. 6) y describe por primera vez la paradoja que enfrenta el sistema, descrita con anterioridad: "*have they [employees] contributed to their own unemployment?*" (¿Deben ellos [los empleados] contribuir a su propio desempleo?) (Hall, 1983, p. 270).

En al año 1988 se traduce al inglés el libro que Ohno que había publicado en japonés en 1978 (Ohno, 1978) y del que solo se había publicado en inglés los primeros capítulos (Ohno, 1982): *Toyota Production System: beyond large-scale production* (Taiichi Ohno, 1988). Aunque la participación de las personas en el sistema está implícita, no propone una estructura para ello; de hecho, describe el

TPS como apoyado en dos pilares: *Just-In-Time* (JIT) y *Jidoka* (automatización con un toque humano).

Como dato ilustrativo, del análisis de los 30 artículos académicos que figuran en Web of Science citando a Sugimori et al. (1977) desde 1977 a 1990, sólo dos lo hacen en consideración al *respect-for human* (Muramatsu et al., 1987; Oliver & Davies, 1990).

En el año 1990 ocurrió un hecho importante en la historia de los Sistemas de Producción Lean. De nuevo en el marco del IMVP, se publicó *The Machine that Changed the World* (La Máquina que cambió el mundo) (Womack et al., 1990) que se convirtió en un *best-seller* mundial. Retomando la denominación propuesta por Krafcik (1988), popularizó el término "*lean production*" en contraposición a la tradicional "*mass production*" (producción en masa). El libro se centra en la evaluación comparativa, sin más referencia al factor humano que la mención de un nuevo paradigma de gestión o como el trabajo en equipo y la involucración de las personas contribuye al mejor resultado del sistema. Incomprensiblemente el texto de Sugimori el al. (1977) no es referenciado ni tampoco se incorporan las aportaciones de Shimada y MacDuffie (1986) sobre la importancia del "*Humanware*".

En este punto encontramos una posible causa para la falta de atención a la parte humana. Como sugiere Magnani et al. (2019) en una de las más reciente revisiones de la bibliografía al respecto (*The Human dimension of lean*), "*Neither Ohno nor Womack, Jones, and Roos have constructed explicitly clear theories concerning the inclusion of the human dimension during lean adoption*" (ni Ohno ni Womack, Jones y Roos han construido una teoría explicita y clara sobre la dimensión humana durante la adopción del Lean) (Magnani et al., 2019). Afirmación que se puede completar diciendo que tampoco Shingo lo hizo. Asimismo, proponen un cambio de punto de vista desde una estrategia puramente "orientada al proceso" a otra "orientada a las personas" y afirman que "es necesario entender mejor el rol de la dimensión humana en una adopción exitosa del *Lean Manufacturing*".

En paralelo con la enorme difusión del concepto "*Lean Production*" en los años 90, aparecieron también algunos trabajos muy críticos relatando el aparente impacto negativo de su aplicación en las condiciones laborales de los trabajadores:

Rehder (1992) denunciaba cómo la Producción Lean, igual que la producción en masa, habían puesto la presión sobre los costes humanos. Como alternativa proponía el Sistema de Producción de Volvo (Rehder, 1992). La historia ha mostrado que este sistema de producción no ha tenido recorrido.

Skorstad igualmente denunciaba pérdida de autonomía e intensificación del trabajo al aplicar Lean Production (Skorstad, 1994).

En la misma línea, otros autores ponían de relieve esta paradoja de que la aplicación del *Lean Manufacturing*, en lugar de respetar a las personas, deterioraba sus condiciones laborales (Williams et al., 1992) (Lewchuk & Robertson, 1996).

Como Hines et al. (2004) sugieren, este enfoque crítico inicial (y paradójico) sobre las negativas consecuencias de la Producción Lean hizo que las primeras investigaciones de los 90 consideraran el Lean más como un conjunto de herramientas técnicas, relegando a un segundo término los aspectos humanos (Hines et al., 2004, p. 998).

Puede ser éste un segundo factor que explique la pérdida de visión holística y el poco recorrido del concepto *respect-for-human*.

A partir de la misma base de datos con la que se ha realizado la SLR del artículo publicado en la revista Applied Sciences (Gil-Vilda et al., 2021) se han identificado los artículos relacionados con el concepto "respect-for-human". Para ello se han seleccionado los que en su título contienen alguna de las siguientes palabras: employee, ergonomic, human, leadership, people, safety, worker, workforce. Después se ha confirmado su contenido mediante la lectura del abstract.

Se han identificado 239 registros (el 4,8% del total). En la figura 1.1 se analizan los artículos/año desde 1992 donde se observa un aumento de interés académico a partir del año 2008. Cabe destacar que precisamente en ese año se publicaron dos libros influyentes que investigan cómo en Toyota se gestiona la parte humana y se asegura la trasmisión del conocimiento y la cultura de una generación a la siguiente: Toyota Talent (Liker & Meier, 2007) y Toyota Kata (Rother, 2009).

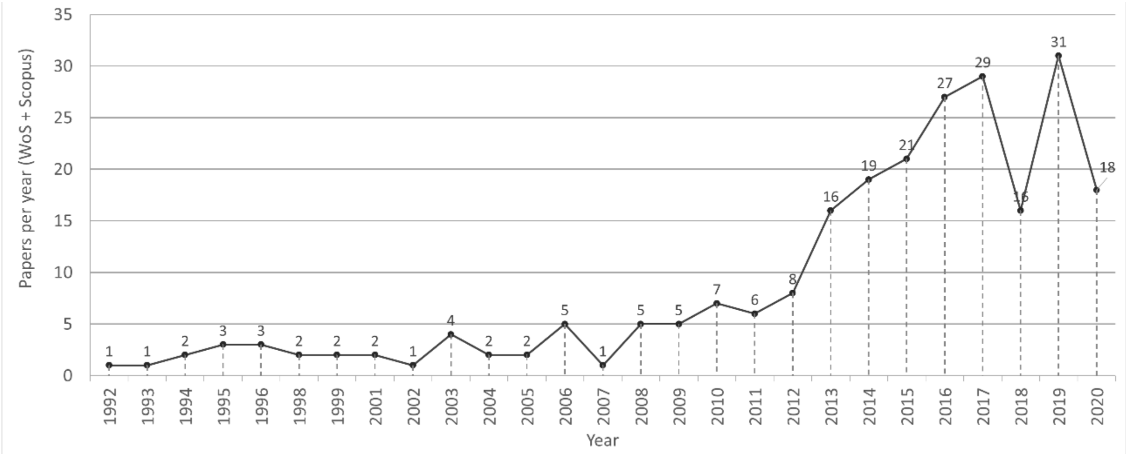


Figura 1.1. *Evolución de los artículos relacionados con el concepto Respect-For-Human.*

Otro ámbito muy ligado al respeto a las personas que también aparece en la revisión bibliográfica, sobre todo a partir del año 2000, es la relación entre Lean, ergonomía y seguridad. Se han encontrado varios enfoques: focalizado en el diseño del entorno de trabajo (Yusoff et al., 2013); más sistémico considerando ergonomía y factores socio-técnicos (Tortorella et al., 2017) ; más ligados a ejecuciones concretas como las células de producción (da Silva et al., 2016) (Botti et al., 2018).

Las investigaciones sobre este tema se muestran también paradójicas como indican Arezes et al. (2015) que, tras una revisión de la bibliografía, concluyen que la mayoría de los autores encuentran tanto impacto positivo como negativo en la mejora ergonómica al aplicar Lean, destacando que los impactos negativos estudiados provienen de malentendidos sobre los principios Lean (Arezes et al., 2015).

Los trabajos más recientes muestran un retorno al concepto indispensable de que el respeto a la persona exige garantizar su salud (Alves et al., 2019) o una propuesta más sistémica que integre Lean, ergonomía y seguridad en el diseño de una estación de trabajo o una línea de producción (Brito et al., 2020), muy en consonancia con la motivación de esta tesis.

Respecto a la medición de la eficiencia del sistema, la literatura se centra mayoritariamente en la Productividad Humana (*Labor Produtivity*). Posiblemente como consecuencia de los trabajos del IMVP que hacían un extenso *benchmarking* sobre este tema, aunque no únicamente; en La Máquina que Cambió el Mundo (Womack et al., 1990) se analiza también de forma comparativa la productividad de la superficie, siendo la única referencia a esta métrica que se ha encontrado en la literatura analizada. Como se ha expuesto, este sesgo refuerza la paradoja descrita poniendo presión sobre las personas. Esta tesis retoma la idea de productividad de la superficie como indicador para medir la eficiencia del sistema.

Tras esta revisión de la literatura se puede concluir que el concepto de "respeto por las personas" utilizado en esta tesis es un concepto fundamental de los Sistemas de Producción Lean desde sus orígenes en el Sistema de Producción Toyota.

Durante la historia de los Sistemas de Producción Lean, desde 1977, la literatura ha prestado poca atención a esta vertiente "*soft*" en relación con el interés por sus herramientas y metodologías "*hard*".

La literatura reporta ampliamente la paradoja de que un sistema que tiene como una de sus condiciones necesarias de éxito el respeto a las personas genera, en ocasiones, entornos laborales más estresantes y menos saludables para las personas, deteriorando en algunas circunstancias la ergonomía física y el bienestar mental. Algunos autores achacan esta situación a un mal entendimiento de los principios lean, a la pérdida de visión de sistema en favor de las partes y a sesgos en la ejecución como forma únicamente de reducir costes de mano de obra. El casi exclusivo interés en la literatura por la productividad humana como métrica para medir la eficiencia del sistema refuerza esta paradoja.

A partir del año 2008, el interés por este concepto ha resurgido y la bibliografía más reciente reconoce esta brecha en el conocimiento y plantea investigar metodologías que la reduzcan.

Esta tesis se enmarca, por tanto, en esta línea de investigación, aportando metodologías de diseño validadas en la práctica que, volviendo a los orígenes del TPS, sitúan al ser humano en el centro del diseño del sistema de producción y buscando una forma de medición de la eficiencia basada en la productividad de la superficie en lugar de la productividad humana.

1.3. Unidad temática.

El hilo conductor de esta tesis es el desarrollo de una metodología de diseño de Sistemas de Producción Lean que asegure el respeto a las personas, sin renunciar a la mejora sistemática de la productividad, la flexibilidad y la excelencia en la calidad.

El método de diseño presentado se ha denominado "*Person-Based Design*" (Diseño desde la persona). Consiste en una metodología de diseño en capas concéntricas (ver Figura 1.2).

El núcleo y punto de inicio del diseño se basa en el respeto a las personas inspirado por la descripción que Sugimori et al. (1977) hace para "*respect-for-human*"; esto es, crear un entorno adaptado a la comodidad del ser humano como base para un sistema eficiente basado en:

- Emplear el esfuerzo humano en tareas valiosas (de valor añadido sobre el producto), evitando operaciones inútiles (derroches).
- Asegurar la integridad de las personas, tanto física como psíquica.
- Desarrollar el potencial humano a través de la participación, la responsabilidad y la involucración.

Para ello, se busca diseñar un entorno alrededor de la persona que sea compacto y ergonómico, orientado al flujo regular del producto unidad por unidad, de forma que el trabajo de la persona se focalice en el valor, eliminando al máximo los 7 derroches de movimientos innecesarios, transportes de producto, stock intermedio, errores de calidad, esperas, procesos innecesarios y sobreproducción.

A partir de este núcleo se diseñan hacia afuera las diferentes capas que constituyen el sistema (ver Figura 1.2):

1. Puesto de trabajo (respeto por la persona).
2. Diseño de embalajes.
3. Herramientas y utillajes.
4. Configuración de la célula de producción.
5. Sistema de aprovisionamiento interno.
6. Almacén.
7. Cadena de suministro desde los proveedores.

La regla clave del diseño consiste en que las acciones que se emprendan para optimizar una capa exterior nunca deben perjudicar la optimización de las capas interiores. Con esta simple regla, si el núcleo del diseño es el respeto por la persona, nunca se tomarán decisiones de optimización que perjudiquen a la persona.

Complementariamente a lo anterior, esta tesis tiene otro nexo en común. Consiste en definir metodologías que, como dirección para conseguir la eficiencia y la mejora del sistema, se basen en la "productividad de la superficie" en lugar de la habitual "productividad humana".

El motivo es coherente con el propósito principal: escoger una métrica de eficiencia que no ponga la presión sobre las personas, pero sirva igualmente de guía para la mejora global del sistema. Adicionalmente, cuando inevitablemente es necesario considerar la mejora de la productividad humana, el foco se pone en la utilización digna del trabajo humano, eliminando tareas innecesarias o penosas para las personas.

Coherente con la metodología inductiva, la tesis se inició alrededor de temáticas muy concretas centradas en la modelización y optimización del entorno próximo a la persona: la línea de producción y en particular las células en U. A esta temática corresponden los que cronológicamente son los dos primeros artículos que se incluyen en esta tesis, ambos presentados en Congresos Internacionales y en las revistas asociadas: MESIC 2017 en Vigo (Gil-Vilda et al., 2017) con publicación en la revista Procedia Manufacturing indexada en el *Scimago Journal Rank* (SJR) y CIRP en Tokyo (Gil Vilda et al., 2018), éste último con publicación en la revista CIRP - Annals indexada en el *Journal Citation Reports* (JCR).

La maduración de los conceptos desarrollados en estos dos primeros trabajos llevó al desarrollo de la tercera publicación (Gil Vilda et al., 2019). En ella se propone un modelo sencillo para describir un Sistema de Producción como un Sistema socio-técnico en el que unos principios (lógica de pensamiento), unas herramientas (metodologías para pasar del pensamiento a la acción), unos métodos (orden adecuado de aplicación de las herramientas) y las personas interaccionan permanente y ordenadamente entre ellos con el objetivo de mejorar la competitividad de una fábrica. En esta misma publicación se propone el método “*person-based design*” (diseño desde la persona) para el diseño del Sistema Productivo partiendo del respeto por la persona. Este artículo fue presentado en el congreso internacional MESIC 2019 en Madrid con posterior publicación en la revista Procedia Manufacturing indexada en el *Scimago Journal Rank* (SJR) (Gil Vilda et al., 2019).

El cuarto artículo en orden cronológico induce, a partir de la observación, una metodología de diseño para el aprovisionamiento que corresponde a la capa 5 del método *Person-Based* Design (ver Figura 1.2). El enfoque innovador consiste en proponer un método orientado a la reducción de superficie en planta y, posteriormente, encontrar un óptimo para la productividad humana que minimice el esfuerzo del conductor del milk-run. Esta publicación fue presentada en el congreso internacional CIRP en Munich en 2020 (Gil Vilda et al., 2020), con la posterior publicación en la revista CIRP – Annals.

La motivación para el quinto artículo surge de la experiencia adquirida revisando la bibliografía de los artículos precedentes que confirmó que, en el mundo académico, como en el industrial, el concepto “Lean” ha caído en el sobreuso y la confusión (Schonberger, 2019). Este último artículo es una Revisión Sistemática de la Literatura (SLR) para indagar en los orígenes y evolución del concepto “Lean” basada en el análisis de 4.962 artículos científicos con la palabra “Lean” en su título y 20 libros seminales frecuentemente referenciados por la literatura académica (Holweg, 2007).

Este quinto artículo (Gil-Vilda et al., 2021) se complementa con el análisis del estado del arte recogido en este documento que, utilizando la misma base de datos de la SLR, presenta la evolución del concepto clave “*respect-for-human*” que sirve como base de la metodología *Person-Based Desing* propuesta en esta tesis.

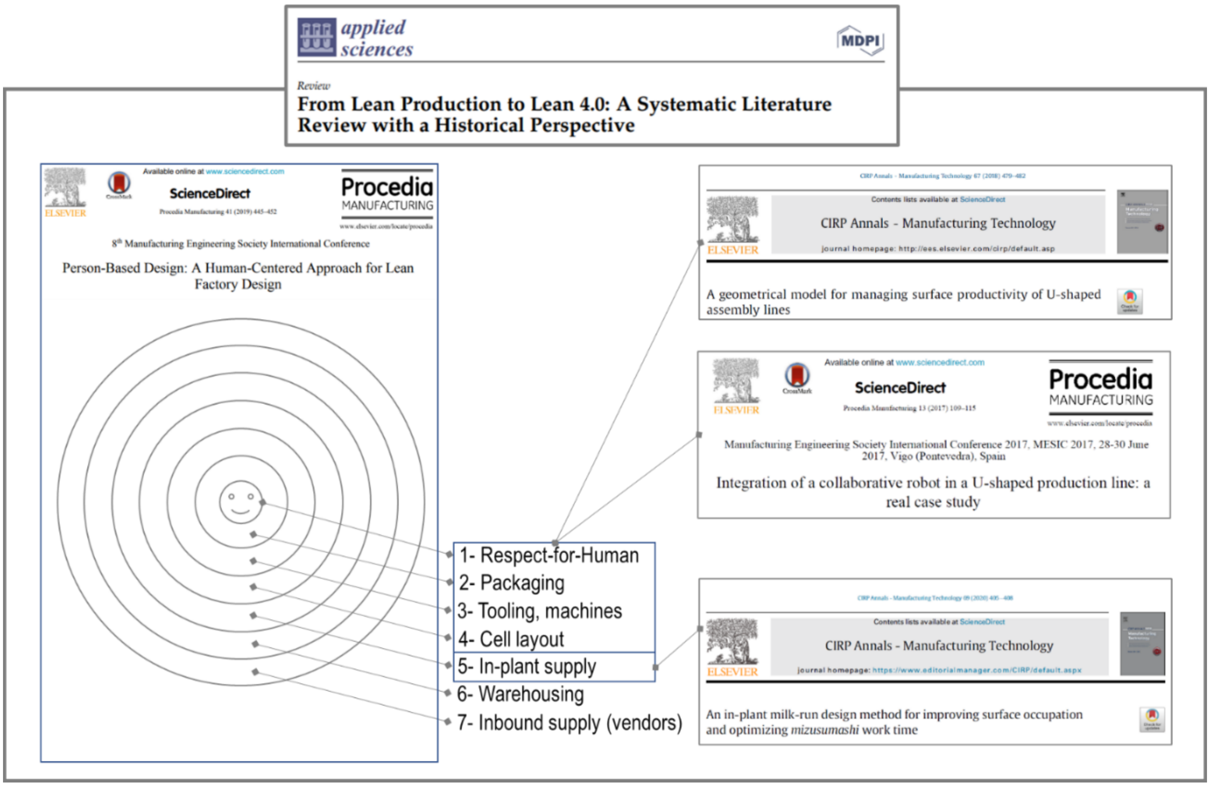


Figura 1.2. *Resumen grafico de la coherencia temática.*

2. Presentación de las publicaciones

A continuación, se presentan los textos íntegros de las publicaciones que constituyen el compendio de artículos de esta tesis.

Con el propósito de dotar de mayor coherencia el desarrollo de los contenidos de esta tesis, los artículos no se presentan en el orden cronológico de su publicación, sino en el orden conceptual.

2.1. From Lean Production to Lean 4.0: A systematic literature review with a historical perspective.

La motivación de este artículo surge del interés por enriquecer la revisión de la literatura de esta tesis incorporando la perspectiva histórica. Los orígenes del término "lean" aplicado a la gestión se remontan ya a más de 70 años. Un tiempo suficiente para poder analizar su evolución histórica, con el aliciente adicional de que el autor ha sido testigo directo de las cuatro últimas décadas.

El trabajo parte de la hipótesis de que el término "lean" en la actualidad se ha vuelto impreciso y, por sobre uso, ha perdido parte de su significado generando cierta confusión.

El objetivo es, por tanto, clarificar el origen y evolución del término "lean". Tanto en lo referente a la evolución de su significado desde su origen como "*Lean Production System*", como en lo referente a la diversificación de su contenido conceptual.

La revisión de la literatura ha confirmado la deriva del significado original. A través de una Revisión Sistemática de la Literatura (SLR) se ha podido trazar con claridad el origen del término Lean, sus antecedentes y su diversificación conceptual. Se han identificado hasta 16 adjetivos calificativos ("apellidos") para modificar el concepto original a través de 4 mecanismo de evolución.

Durante el trabajo de búsqueda bibliográfica para el artículo, se analizó en paralelo la evolución del concepto seminal "*respect-for-human*"; las conclusiones se han incorporado al estado del arte de esta tesis.

El resultado de esta revisión sistemática de la literatura es una visión coherente del concepto "Lean" y su concreción en el campo industrial, que es donde se han desarrollado los restantes artículos de este compendio, así como las metodologías que son objeto de esta tesis.

applied sciences

Review

From Lean Production to Lean 4.0: A Systematic Literature Review with a Historical Perspective

Francisco Gil-Vilda [1], José A. Yagüe-Fabra [2,*] and Albert Sunyer [3]

[1] LEANBOX SL, Distrito 22@. C/Juan de Austria 126, 08018 Barcelona, Spain; francisco.gil.vilda@leanbox.es
[2] I3A—Universidad de Zaragoza, C/María de Luna, 3, 50018 Zaragoza, Spain
[3] ESEIAAT—Universitat Politècnica de Catalunya, C/Colom, 11, 08222 Barcelona, Spain; albert.sunyer.torrents@upc.edu
* Correspondence: jyague@unizar.es

Abstract: Over recent decades, the increasing competitiveness of markets has propagated the term "lean" to describe the management concept for improving productivity, quality, and lead time in industrial as well as services operations. Its overuse and linkage to different specifiers (surnames) have created confusion and misunderstanding as the term approximates *pragmatic ambiguity*. Through a *systematic literature review*, this study takes a historical perspective to analyze 4962 papers and 20 seminal books in order to clarify the origin, evolution, and diversification of the lean concept. Our main contribution lies in identifying 17 specifiers for the term "lean" and proposing four mechanisms to explain this diversification. Our research results are useful to both academics and practitioners to return to the Lean origins in order to create new research areas and conduct organizational transformations based on solid concepts. We conclude that the use of "lean" as a systemic thinking is likely to be further extended to new research fields.

Keywords: lean manufacturing; lean production systems; lean 4.0; systematic literature review

Citation: Gil-Vilda, F.; Yagüe-Fabra, J.A.; Sunyer, A. From Lean Production to Lean 4.0: A Systematic Literature Review with a Historical Perspective. *Appl. Sci.* **2021**, *11*, 10318. https://doi.org/10.3390/app112110318

Academic Editor: Maurizio Faccio

Received: 6 October 2021
Accepted: 29 October 2021
Published: 3 November 2021

1. Introduction

Over recent decades, markets have become more and more competitive as they progressively demand customized products and services at lower prices and with shorter delivery times [1]. In the operations field, lean has become a widespread management system that is suitable for achieving these competitiveness targets [2–4] through more efficient processes, shorter lead times, and greater flexibility in supplying a wide variety of products and services in small quantities [5].

As a consequence, the management concept of lean has spread profusely throughout industry and services over the last 40 years [3]. A huge amount of research is now available for scholars and practitioners, with the present work having identified 4962 academic papers with "lean" in the title and "lean manufacturing" generating 8,910,000 results through a Google search.

When a term becomes popular and fashionable, its overuse runs the risk of devaluing its original meaning and may create inconsistencies and ambiguities [6,7]. In addition, the term "lean" leads to more semantic confusion because it is frequently joined with specifiers by way of "surnames" related to a wide variety of fields and uses.

In practice, the term "lean" approximates *pragmatic ambiguity*, as described by Giroux [8] and similarly assessed in terms of the lean culture concept by Dorval et al. [9]. What is even worse, as Schonberger recently warns [7], it may be in risk of disintegration.

Indeed, this misunderstanding is one of the issues that lean practitioners face when implementing an organizational change and they need to align lexicon and terminology with common conceptions [4].

The objective of this study is to provide a historical perspective on the lean concept by clarifying its origins, evolution, and how it became diversified from its original concept up until today. Furthermore, this research aims to help scholars, practitioners, and managers seeking to return to the lean origins in order to better understand the evolution and current state of this field of knowledge.

From a methodological point of view, this research has followed the principles of the systematic literature review (SLR). Templier and Paré [10] have classified literature reviews into four types: narrative (summarizes previous published research); developmental (provides new conceptualizations or methodological approaches); cumulative (compiles empirical evidence and draws conclusions about a topic of interest); and aggregative (tests specific research hypotheses or propositions, with three subtypes: systematic, meta-analysis and umbrella review). The historical approach of this research falls under both cumulative and aggregative literature reviews.

Tranfield et al. [11] propose methodologically adapting SLR from medical science to management science, while Denver and Transfield [12] developed their method even further. SLR has been used in previous studies on lean topics [3,4,9,13–15]. This study follows the SLR methodology as defined by Denver and Tranfield [12], and it uses the PRISMA 2020 checklist [16] to ensure that a rigorous SLR process has been used.

2. Materials and Methods

We conducted an SLR in accordance with the five steps proposed by Denyer et al. [12]: question formulation; locating studies; study selection and evaluation; analysis; synthesis; reporting; and using results.

2.1. Question Formulation

As introduced above, this study aims to answer the following research questions:

- RQ1: What is the historical origin of the term "lean"?
- RQ2: What are the previously used terms (if any) for the lean concept?
- RQ3: How has the term "lean" evolved over time?

2.2. Locating Studies

Three bibliographical materials have been used:LISTORDE

1. English language records at the Web of Science database from 1950 to 2020.
2. English language records at the Scopus database from 1987 to 2020.
3. Books: We analyzed a collection of 20 seminal hardcopy books published between 1977 and 2020.

2.2.1. Locating Database Records

As proposed by Sinha et al. [17] (p. 304), we searched for the keyword "lean" in titles to ensure our focus on both the historical interest and evolution of the topic. A first search on Web of Science conducted on 5 January 2021 provided 13,558 records containing the word "lean" in the title. An initial quick review showed that "lean" is a popular term in other disciplines too. Therefore, our search was refined to some related WoS categories. The final search string is shown in Figure 1.

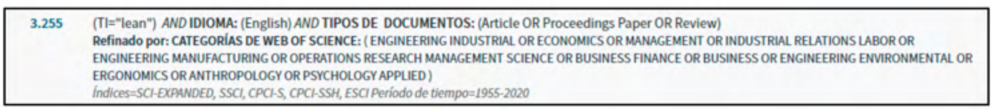

3.255 (TI="lean") *AND* **IDIOMA:** (English) *AND* **TIPOS DE DOCUMENTOS:** (Article OR Proceedings Paper OR Review)
Refinado por: CATEGORÍAS DE WEB OF SCIENCE: (ENGINEERING INDUSTRIAL OR ECONOMICS OR MANAGEMENT OR INDUSTRIAL RELATIONS LABOR OR ENGINEERING MANUFACTURING OR OPERATIONS RESEARCH MANAGEMENT SCIENCE OR BUSINESS FINANCE OR BUSINESS OR ENGINEERING ENVIRONMENTAL OR ERGONOMICS OR ANTHROPOLOGY OR PSYCHOLOGY APPLIED)
Índices=SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH, ESCI Período de tiempo=1955-2020

Figure 1. Web of Science search string.

This second bounded search on 5 January 2021 provided a total of 3255 records, which we transferred to a spreadsheet for analysis and classification.

In a first analysis, the most cited studies were analyzed [1,5,6,8,18,19] to uncover any general agreement on the origins of the term "lean" in the field of management, by which we found it was first coined in 1988.

Even though records from 1950 to 1988 were reviewed, only one similar and metaphorical use of "lean" was found [20]: "Managerial Productivity: Who Is Fat and What Is Lean?". However, this instance in management research was not fully associated with its later use in operations management where it was fully developed.

We performed a manual review based on the WoS category and title analysis in order to remove any records of non-related topics (e.g., combustion, food, information, chemicals, etc.). Works published ahead of print (early access) were discarded. Finally, 2932 records were retained for further analysis.

Similarly, a Scopus database search was made on the same date (5 January 2021) for studies published in the English language after 1987, restricting these to items labelled as articles, conference papers, and reviews. These were further limited to the subject areas of business, management, and accounting. The Scopus search string is shown in Figure 2.

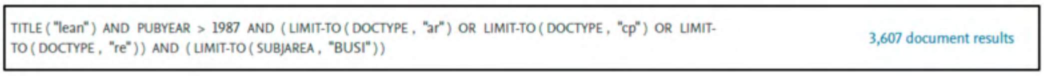


Figure 2. Scopus search string.

The records were transferred to a spreadsheet, merged with those from the WoS search, and redundancies were removed. Finally, a total of 4962 records were kept for further analysis.

A first manual review based on reading the titles and, if necessary, the abstract allowed us to determine the selection criteria for the records, as described in Section 2.3.

The SLR process is shown in Figure 3.

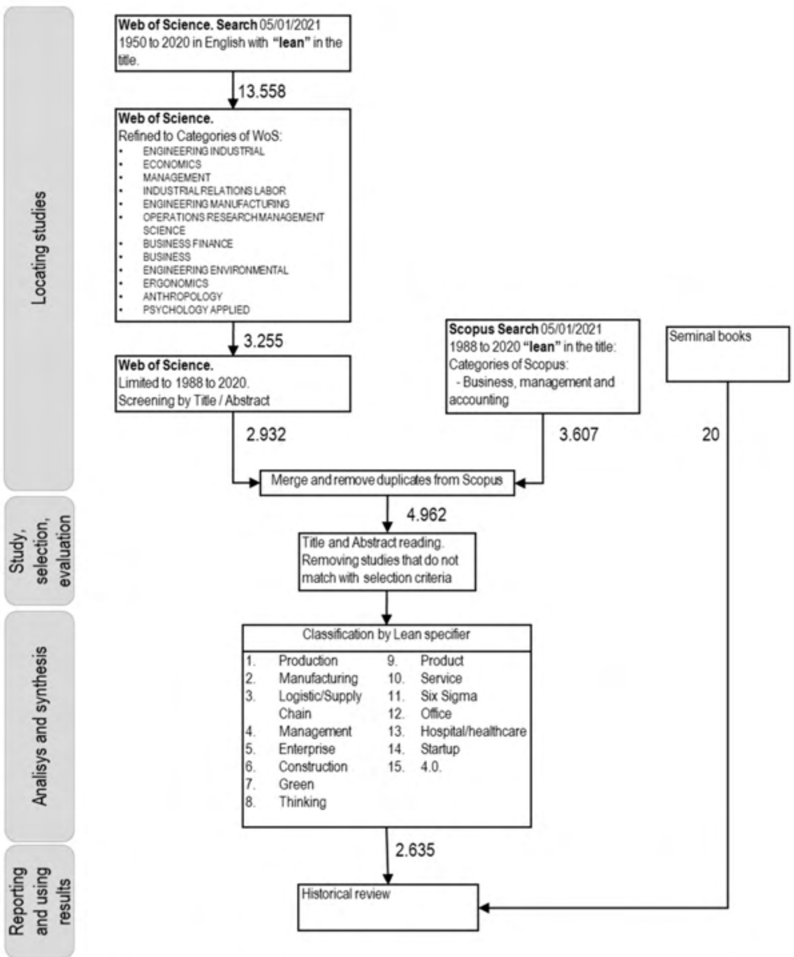


Figure 3. SLR process overview.

2.2.2. Books

Books were collected based on the Holweg's list [19] (p. 434), new titles were added to this list. A total of 20 seminal hardcopy books were analyzed. Books were gathered from private collections or were acquired at https://www.bookfinder.com/ (accessed on 5 September 2021).

2.3. Study Selection and Evaluation

To select the relevant records associated with the research questions, their titles and abstracts were analyzed. The following selection criteria were defined:

- The title allows confirming that the term "lean" is used as a managerial concept.
- The abstract confirms that the term "lean" is related to operations management.

To avoid bias, if neither title nor abstract allowed classifying the record, it was removed.

2.4. Analysis and Synthesis

After selection was done, the database records were analyzed based on the bibliometric measure "papers-per-year" (Figure 4).

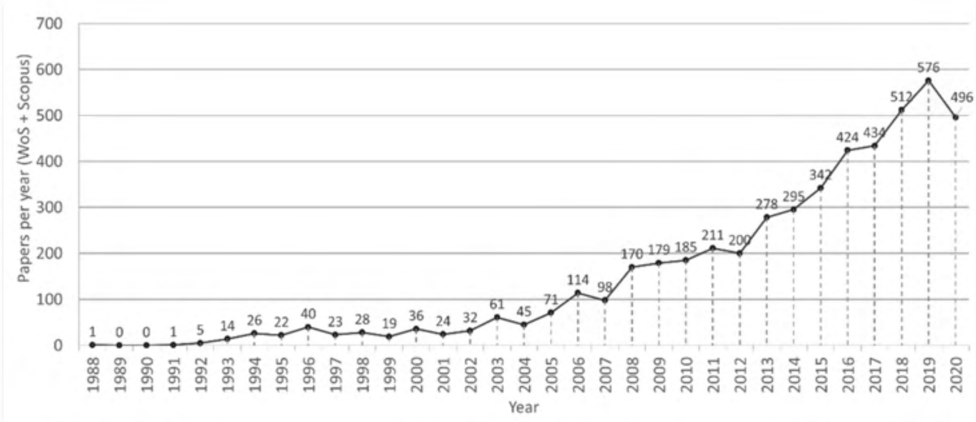


Figure 4. Evolution of papers per year that include "lean" in the title over the study period (1988–2020).

During our analysis of the titles, the main lean specifiers ("surnames") were found and we accordingly classified the records under the following categories (by chronological order of appearance): production, manufacturing, logistics/supply chain, management, enterprise, construction, green, thinking, product, service, six sigma, office, healthcare/hospital, start up, 4.0.

To facilitate the historical analysis, we created a general chart split into categories (Figure 5): the most relevant categories are represented by a line starting at the year of their foundational paper or book; the line thickness is proportional to the paper-per-year bibliometric (see scale in the same Figure 5).

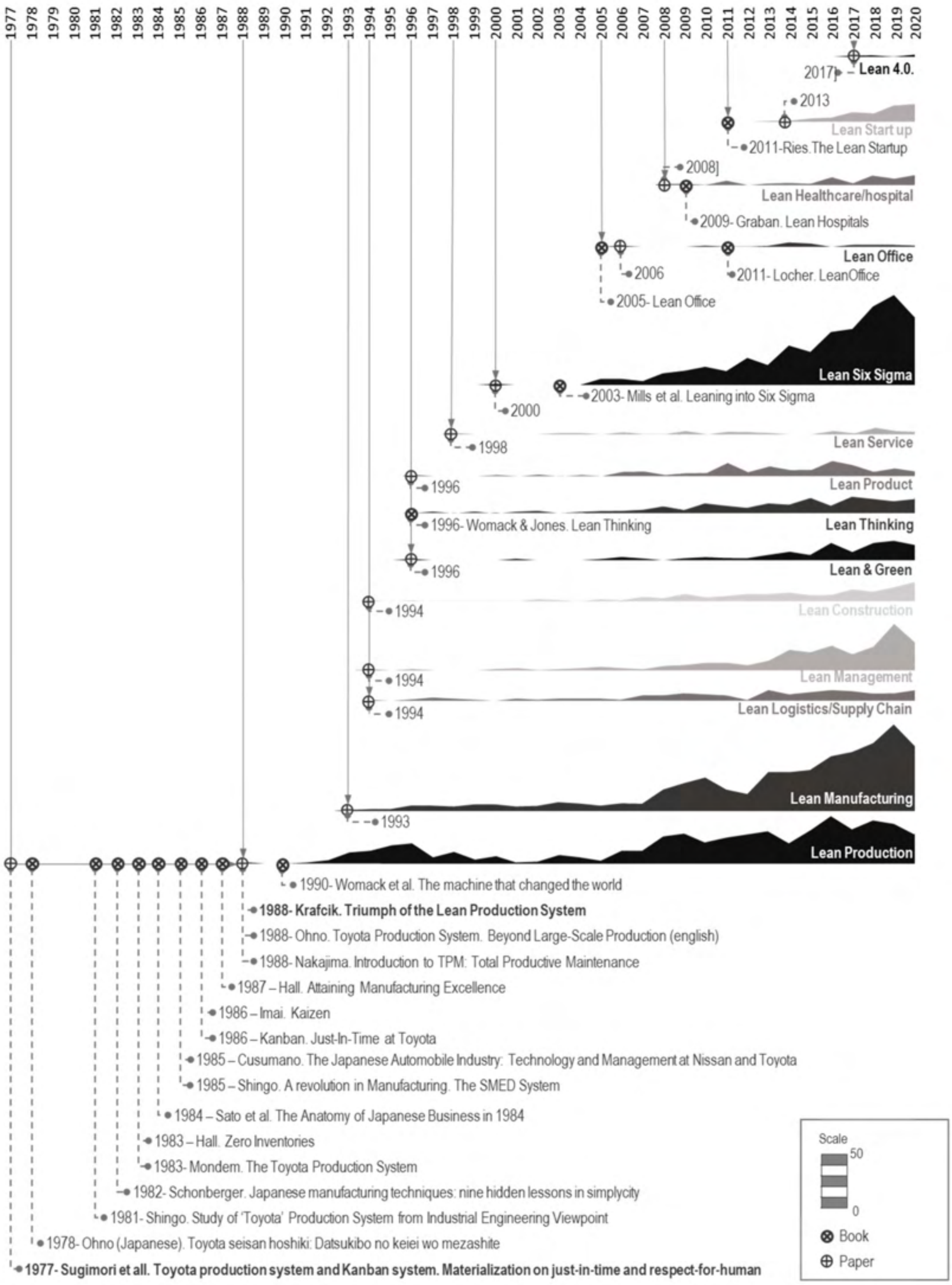


Figure 5. Historical evolution of the main lean categories and their foundational works.

3. Results

3.1. Origin and Previously Used Terms for the Lean Concept in Operations Management

In answering RQ1 (What is the historical origin of the term "lean"?), we found a general consensus [1,2,6,13,19,21,22] that the term "lean" was coined in the International Motor Vehicle Program (IMVP) and published for the first time in 1998 by John F. Krafcik, in the academic paper titled *Triumph of the Lean Production System*, when he stated "lean typology builds on the work of International Motor Vehicle Program researchers Haruo Shimada and John Paul Max Duffie, who use the terms 'robust' and 'fragile' to denote similar concepts" [23] (p. 51). Here, Krafcik is referring to the 1986 working paper *Industrial Relations and "Humanware"* [24].

The word "lean" was chosen for its more positive sense [19] (p. 426) or, as suggested by New, "as an acceptable way of describing Toyota production system without offending the other sponsors of the IMVP" [22] (p. 3547).

Therefore, to answer RQ2 (What are the previously used terms (if any) for the lean concept?), we must return to the foundations of the Toyota Production System. There is wide agreement [5,6,9,22] that the first English language paper introducing the term "Toyota production system" (TPS) was presented in Tokyo by Sugimori et al. in 1977 [25]: *Toyota Production System and Kanban System. Materialization of Just-in-Time and Respect-for-Human System*. This seminal paper based TPS on two pillars: just-in-time and respect-for-humans. The authors acknowledged Taiichi Ohno as having been the promoter and leader of TPS since at least 1957.

Ohno's seminal 1978 book (published only in Japanese) was *Toyota seisan hoshiki: Datsukibo no keiei wo mezashite* [26], and his first paper translated to English dates back to 1982 [27] (*How the Toyota Production System Was Created*, republished in The Anatomy of Japanese Business in 1984 [28]). This early translation offered an alternative and more accurate translation to just-in-time: "right on time" which was not adopted.

The first book in the English language describing TPS was published in 1981 by Shigeo Shingo: *Study of "TOYOTA", Production System from Industrial Engineering Viewpoint* [29]. He acknowledged Ohno as the promoter of TPS (pp. 19–32) and postulated that his own book would provide a more practical explanation. It was a highly influential book in which Shingo insisted repeatedly on an essential systemic view in order to understand TPS. This book was republished with a better English translation in 1989 by Productivity Press [29].

In 1983, Yasuhiro Monden published *Toyota Production System: Practical Approach to Production Management* [30]. The foreword by Ohno highlighted the excellent conceptualization of the TPS. Without losing the holistic vision, tools and methodologies were profusely described.

The first Western researchers interested in the topic were very influenced by these early books, and they published their works in the period between 1983 and 1988, during which different "nicknames" were used to refer to the TPS:

- *Japanese Manufacturing Techniques*, by Schonberger (1982) is the first book written in English and it described "stockless production" and "JIT Production" [31] (p. 17).
- Hall, in his book *Zero Inventory* (1983) [32] (p. 1) adopted the term "stockless production". In another book, *Attaining Manufacturing Excellence* (1987) [33] (p. 23), he summarized the most used terms at the time: "manufacturing excellence", "value-added manufacturing", "continuous improvement manufacturing", and "JIT/TQ".
- Cusumano's book *The Japanese Automobile Industry* (1985) [34] (pp. 262–307) described the foundations and evolution of TPS with a historical perspective, although he did not propose any alternative terms.
- In the context of IMTV, "fragile production" was already being used in 1986 [24].

From 1985 to 1990, different TPS tools were documented in detail, thus providing progressively greater understanding but fragmenting the overall vision by "using the part for the whole", as Shah [6] (p. 786) suggested. Some examples of these TPS tools are: SMED (1985) [35], Kanban (1986) [36], Kaizen (1986) [37], and TPM (1988) [38].

In 1988, the English translation [39] of Ohno's [26] book was published: *Toyota Production System: Beyond Large-Scale Production*.

To summarize the answer to RQ2, the lean production system can be considered a way of naming the Toyota production system without naming Toyota. With the same intention, other terms were proposed prior to 1988 by taking some of the more relevant parts of the system as inspiration: *Japanese manufacturing techniques, stockless production, JIT production, value-added production, continuous improvement manufacturing, non-stock production, fragile production*.

3.2. Answering RQ3. Historical Evolution of the Term "Lean"

As already pointed out, the expression "lean production system" was coined by Krafcik in 1988 [23]. The seminal and best-selling book, *The Machine that Changed the World* [21], popularized the term "lean production"; and earlier similar expressions were completely abandoned (with the only exception being just-in-time, which survived in the supply chain literature until now).

Womack et al. [21] used the term "lean production" in contrast to "mass production" with the intentions of setting a benchmark, although the original systemic vision was lost. This is probably the first symptom of the "lack of distinction between the systems and its components" as Sha et al. [6] suggested.

Thus, 1990 can be considered the year when the term "lean" became popularized as an operations management concept. From 1990 to 1995, the term "lean" was adopted in the literature mainly as "lean production". The first research papers focused on either supporting or questioning lean [40–42] while describing the first lean experiences and the limits of this practice [42].

In 1991, Delbridge et al. [43] introduced "lean manufacturing" as a synonym for "lean production", and this term became more popular after 2000. Nowadays, "lean manufacturing" is the preferred expression for referring to lean in industrial operations (Figure 5).

From 1992 to 1996, some authors intended to upgrade lean to a more conceptual level by introducing the terms "lean management", "lean enterprise" [44], and "lean thinking" [45]. This opened the door to using the term in non-manufacturing contexts, such as the services sector.

In parallel, the period 1994 to 2000 saw the first attempts to apply lean to different production contexts (lean construction) as well as to others outside pure production (lean logistics, lean supply chain) or by combining it with supplementary topics (lean and green, lean product, lean six sigma). The fragmentation of the lean system into its tools continued with books such as *Lean Toolbox* [46]

It was not until 2005 that the lean concept opened its scope to the services sector, mainly under the umbrella of lean six sigma, lean office, lean healthcare/hospital, and, recently, lean startup.

Finally, in 2017, lean 4.0 appeared as a promising way for new developments by fusing lean and Industry 4.0 technologies.

All in all, the term "lean", which was initially conceptualized as a "lean production system", has evolved from 1988 to 2020 as a "living concept". This evolution can be ascribed to the following proposed mechanisms that mostly combined with each other over time:

- Expansion: extending the concept in the operations field.
- Transfer: applying the concept beyond production.
- Targeting: focusing the concept on a particular sector.
- Combination: merging the concept with other concepts.

Through analyses of the scientific literature, this work has identified the most important lean specifiers ("surnames"). They are presented in chronological order of their appearance and describe (a) the first record found in our database analyses; (b) the historical trajectory based on the most relevant publications; (c) the evolution mechanisms; and (d) the present situation in terms of research interests. A chart with the yearly evolution of papers-per-year complements the summary.

3.2.1. Lean Production (1988)

Introduced in 1988 by Krafcik as the "lean production system" [23], this expression was used as an alternative to the "Toyota production system". It was fully adopted after publication of the seminal book *The Machine that Changed the World* [21], which described lean production (LP) as an alternative to mass production [2], whereby the original holistic approach of TPS was partially lost.

Interest in LP grew between 1992 and 1996 (see Figure 6), then diminished from 1997 to 2007. Since 2008, it has once again become of academic interest, along with lean manufacturing.

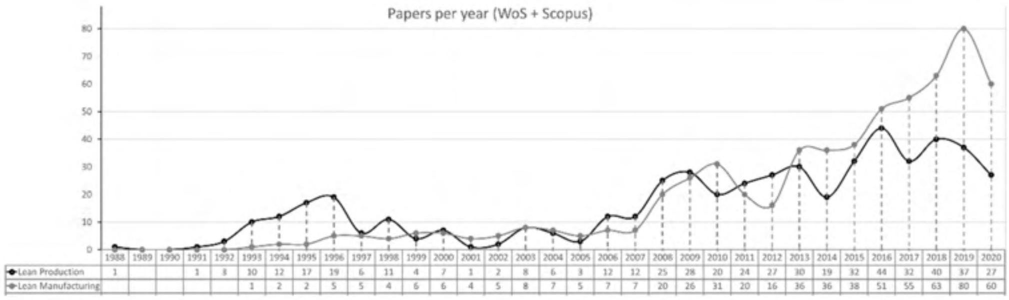


Figure 6. Lean production vs. lean manufacturing evolution.

In 2007, Holweg [19] outlined a detailed historical evolution of the term, which was highly influenced by MIT research. The same year, Sha et al. [6] analyzed the historical context and reported for the first time the semantic confusion surrounding the term "lean production" while also reinforcing the conception of lean "as a system", for which he identified 10 dimensions useful to researchers.

In 2013, Marodin et al. [47] identified six research areas in the field and provided another warning about the system conception becoming fragmented and dissociated. In 2015, Jasti et al. [1] concluded that LP continues to have a high impact on academia, practitioners, and consultants. They further propose a holistic rather than "bits-and-pieces" approach [1] (p. 16).

In 2015, *The Analysis of Industry 4.0 and Lean Production* [48] presented the first comparative study between LP and I4.0. With 17 papers published in the last 5 years, the interrelationship between LP and I4.0 has clearly awakened new interest in this research field [49,50].

3.2.2. Lean Manufacturing (1993)

In 1993, Powell introduced lean manufacturing (LM) in a similar sense to lean production: *Lean Manufacturing Organization, 21st Century* [51].

In 2003, [52], Shah et al. also used this term with the same meaning as lean production and focused the topic on factory management. In 2013, Bhamu et al. [5] presented the evolution of LM definitions.

The most recent main reviews of lean manufacturing that confirm this equivalence with lean production were published between 2019 and 2020 [3–5,53]. These reviews are perhaps targeted more to the fields of industry and, specifically, factory management.

In 2016 [54], the first linkage with Industry 4.0 was made. Until 2020, the relationships between LM and Industry 4.0 were explored. In the last one, published in 2020 [55], Valamede et al. offered a holistic view toward integrating both concepts.

As a conclusion, lean manufacturing can be considered synonymous with lean production, although targeted more at factory operations. After 2000, is the preferred term in the academic literature when referring to lean in the industrial field (Figure 6). That is probably to distinguish the production of goods, since the term "production" is used more and more in the service industries.

3.2.3. Lean Logistics (1994), Lean Supply (1996) and Lean Supply Chain (1999)

The first paper on lean logistics (LL) was authored by Fynes et al. in 1994, *From Lean Production to Lean Logistics: The Case of Microsoft Ireland* [56], which illustrated the expansion from production to supply chain management.

In 1996, the first paper to use using "lean supply" was *Squaring Lean Supply with Supply Chain Management* [57], in which the authors extended the concept to supply chain management.

In 1999, the first paper to use "lean supply chain" (LSC) was *Vertical Integration in a Lean Supply Chain: Brazilian Automobile Component Parts* [58], which related the term "lean" to a broader perspective on supply chain management.

The three surnames can be considered quite equivalent, in that they focus on: the efficiency of material flows inside and outside the factory; the integration and development of suppliers; and the integration of different actors and information across the supply chain [59].

García Buendía et al. (2020) [60] presented a conceptual evolution map of the concepts behind lean supply chain management over the last 22 years.

Relationships between lean supply chain and I4.0 have appeared in recent years in publications on different topics, such as the impact of these on performance improvement [61–64] and their further relationships with information and digital technologies [63].

To conclude, these specifiers appeared as lean expanded to supply chain management: "Lean logistics [. . .] is based around extended TPS right along supply chain from customers right back to raw material extraction" [64] (p. 171).

The three surnames in this field extend lean perspective to supply chain management, with interest having increased moderately since 2007 (Figure 7).

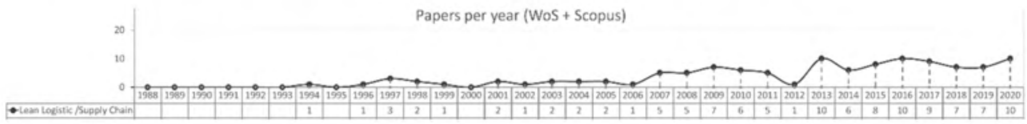


Figure 7. Lean logistics and lean supply chain evolution.

3.2.4. Lean Management (1994)

The origins of the term "lean management" (LMg) are unclear. The first reference in the English language academic literature was introduced by Petrovic et al. in 1994: *Business Process Re-Engineering as an Enabling Factor for Lean Management* [65]. Nevertheless, the German literature has used this term since 1992. It seems to be a first attempt at shifting towards a more managerial concept in a similar way as the later emergence of lean enterprise or lean thinking.

In any case, it was not until 2008 that the literature showed consistent interest in the topic.

In 2014, Martinez-Jurado et al. [66] presented the term in association with organizational sustainability. More recently in 2019, Sinha et al. [17] considered lean management to be an extension "into an inter-disciplinary subject with linkages to operations management, organizational behaviour, and strategic management".

In 2016, the first paper on LMg and I4.0 was published: *Industry 4.0. The End Lean Management?* [67], concluding at the time that the correlations between both concepts were low.

As a conclusion, lean management can be considered as a transfer to a more managerial approach. It refers to adopting lean principles in order to manage an entire organization. Although quite neglected until 2008, it has generated growing interest in the past decade, at least, up until 2019 (Figure 8).

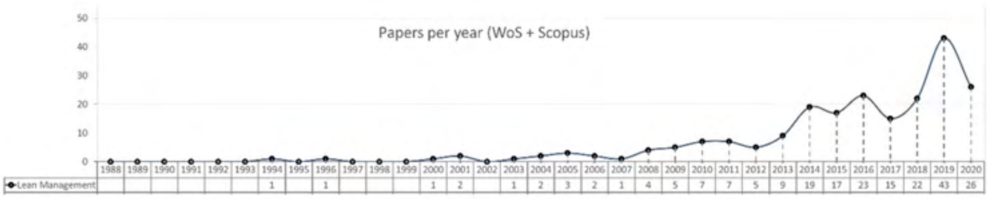


Figure 8. Lean management evolution.

3.2.5. Lean Entreprise (1994)

The expression “lean enterprise” (LE) was coined in 1994 by Womack and Jones in their book *From Lean Production to the Lean Enterprise* [44], in which lean shifts toward a more abstract concept: “the lean enterprise is a group of individuals, functions, and legally separate but operationally synchronized companies that creates, sells, and services a family of product”.

As a conclusion, lean enterprise can be considered a transfer to a more abstract concept. The term has not been widely adopted in literature, but it remains alive, as evidenced in the last review published in 2020 [68] and the first proposals linking LE with 4.0 technologies [69] (Figure 9).

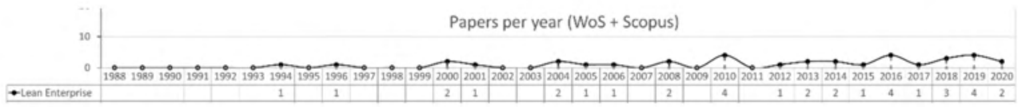


Figure 9. Lean enterprise evolution.

3.2.6. Lean Construction (1994)

The first indexed reference to lean construction (LC) dates back to 1994, when Koskela published the proceedings paper *Lean Construction* [70], which placed lean production in the particular context of a product (a building) that cannot be moved in a continuous flow.

It was not until 2002 when research attention returned to the topic [71], and in 2006 Salem et al. [72] proposed a practical view toward implementing lean tools.

In 2019, Koskela presented an epistemological perspective not only on LC but also on lean and its Japanese origins [73]. In 2020, Lekan et al. [74] proposed “Construction 4.0” as the link between LC and “Industry 4.0” with the aim to go further in construction operations efficiency.

The last review [75] was published in 2020, and it explored the barriers to implementing LC.

As a conclusion, lean construction targeted this specific sector in which the product cannot be moved in a continuous flow. It adapts lean principles and tools to this particular production process. It was quite ignored until 2008, but the topic has generated moderately increasing interest in the past decade, recently linked with I4.0 (Figure 10).

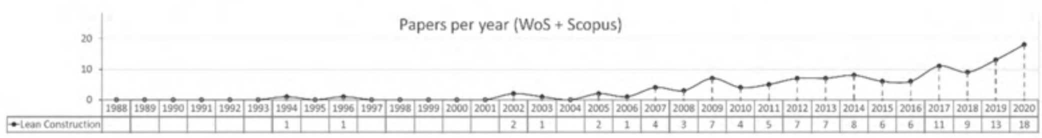


Figure 10. Lean construction evolution.

3.2.7. Lean and Green (1996)

Lean and green (L&G) appeared in a 1996 Florida publication [76]: *Lean and Green: The Move to Environmentally Conscious Manufacturing*. It integrates process improvements with reductions in environmental impact.

The first publications on L&G focused on how to establish a link between lean principles and environmental practices, with an emphasis mainly on manufacturing [77] and supply chain management [78].

Interest in the topic has increased since 2013, and the first literature review (in 2015) [79] proposed it as a specialized research area. In 2019, Farias et al. developed a systemic approach [80,81].

Recently the scope has been extended to products and services [82], as well as combined with Industry 4.0 issues [83,84]

As a conclusion, lean and green (sometimes green lean) emerged as a combination with environmental and sustainability concepts. It refers to the synergy between lean and environmental preservation. More specifically, it focuses on how lean practices can contribute to reducing environmental impact while maintaining profits primarily in operations, but also in services and product design. The topic has generated increasing research interest since 2013 (Figure 11).

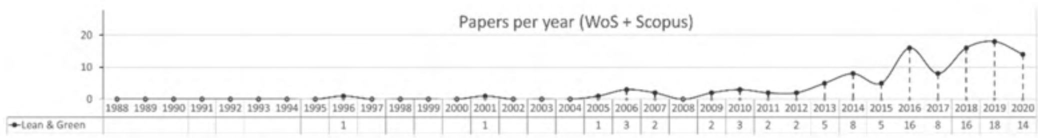


Figure 11. Lean and green evolution.

3.2.8. Lean Thinking (1996)

Lean thinking (LT) was introduced in 1996 by Womack and Jones [45] in their best-selling book *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. With intentions similar to lean enterprise, the term can be considered a shift toward a philosophy of eliminating waste in organizations. This way of thinking is structured in five steps: specify value; identify the value stream; flow; pull; and pursue perfection.

The first indexed article is from 1997 [85], and it analyzes the impact of LT and LE on the marketing processes. In 2004, Hines et al. [18] published a very detailed study on the topic, beginning with its genesis and moving on to identify both the successes and difficulties of Western companies applying LT. The last review was published in 2020 [86], and it explored the synergies between LT and Industry 4.0 while further suggesting how LT could trigger I4.0 solutions.

As a conclusion, lean thinking is a transfer to a more abstract approach. It refers to adopting a way of thinking in order to make radical improvements in any organization. Research interest in this topic has remained moderate and stable in the past decade (Figure 12).

Figure 12. Lean thinking evolution.

3.2.9. Lean Product (1996)

The first paper, *The Difficult Path to Lean Product Development*, by Karlsson et al. [87], introduced the expression “lean product” in 1996 as an extension to product development. It refers to fast, efficient, and low-cost product development [88].

The concept was created for physical goods and generated low interest among researchers until 2006. The same year, Liker et al. [89] proposed the concept in order to go “beyond manufacturing to any technical or service” with a systemic view toward “integrating people, process and tools”.

The first review in 2011 [88] showed the historical links between LP and TPS while presenting a list of conceptual principles.

In 2015, Sassanelli et al. [90] introduced a systemic view that focused particularly on services as a lean product service system. This approach was recently analyzed in the latest systematic reviews on the topic [91].

As a conclusion, lean product extends to product development in terms of both goods and services. It has generated moderate and stable interest since 2006 (Figure 13).

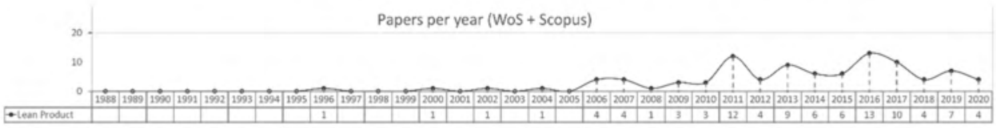


Figure 13. Lean product evolution.

3.2.10. Lean Service (1998)

Lean service (LSe) was proposed in 1998 by Bowen et al. in their article *Lean Service: In defense of a Production-line Approach* [92] in order to extend lean to industrial services. The next indexed paper was published in 2003: *The Lean Service Machine* [93], which adapted lean production to an insurance company (JPF).

LSe refers to applying lean principles and tools toward the improved efficiency of non-manufacturing services [94] such as insurance firms [93], call centers [95], financial services [96], banking, and healthcare services [97].

A systematic review published in 2016 [98] concluded that lean was applicable in services with limitations, and it identified LSe as a nascent research area.

As a conclusion, lean services transfer from manufacturing to service processes. It refers to applying lean manufacturing principles and tools that have been adapted to services production. Researchers have shown little interest in it, probably because this perspective is also explored by lean six sigma scholars (Figure 14).

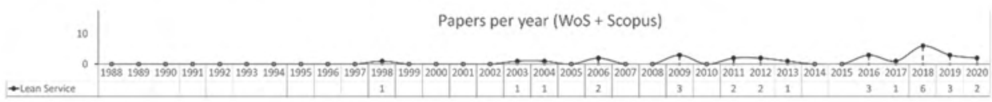


Figure 14. Lean services evolution.

3.2.11. Lean Six Sigma and Lean Sigma (2000)

The first published reference to this field appeared in 2000 as "lean sigma" [99] in the article "*Lean Sigma Synergy*"; but it was not until 2005 when the first indexed paper used "lean six sigma" (LSS) as "an approach focused on improving quality, reducing variation and eliminating waste in an organization" [100].

Lean six sigma merged lean and six sigma, which are two disciplines that, if not in opposition to each other, were at least in competition until 2003. In this year, the book *Leaning into Six Sigma* [101] attempted to join together the best practices from lean and six sigma [102].

After 2005, the concept has generated increasing interest among researchers, as shown in the evolution of published papers (particularly after 2013) in contexts of both manufacturing [103] and service [104]. Recent research has shown interest in the links with Industry 4.0 [105,106].

As a conclusion, lean six sigma and lean sigma is a combination of the principles and tools from lean manufacturing (reducing waste) and six sigma (reducing variability and promoting leadership). Originally created for manufacturing industries, it extended its implementation to services too. Interest in this topic has increased sharply between 2004 and 2019 (Figure 15).

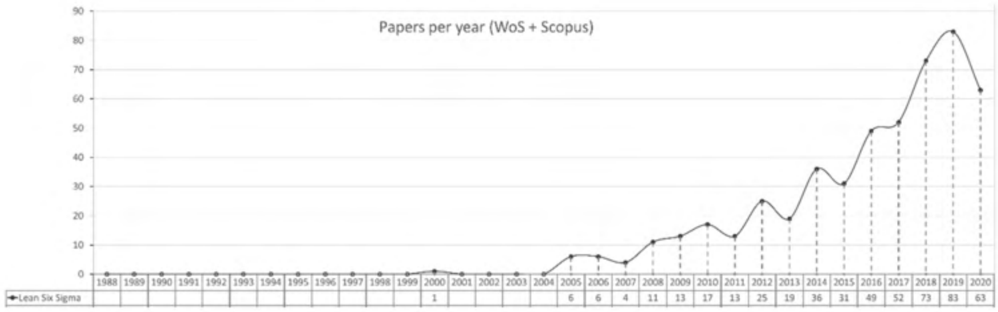


Figure 15. Lean six sigma evolution.

3.2.12. Lean Office (2005)

Lean office (LO) appeared in 2005 with the book *The Lean Office* [107], collecting practical cases from 2000 to 2004 of extending lean to non-manufacturing environments.

In 2011, Locher published *Lean Office* [108] with a methodological and holistic approach to apply lean in services, commercial and administrative environments.

The very limited academic literature available starts on 2006 with Herkommer et al., *Lean Office-System* [109] and focuses on surface optimization, workplace improvements [110], and information flows in administrative processes [111]. A systematic literature review published in 2019 [112] described implementation issues and areas of research.

As a conclusion, lean office is a transfer to non-manufacturing environments with a focus on improving efficiency at the administrative level. The scant academic interest in this topic lies in stark contrast to the term's popularity among practitioners (Figure 16).

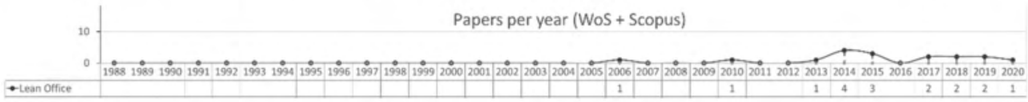


Figure 16. Lean office evolution.

3.2.13. Lean Healthcare/Hospital (2008)

In 2008, Portioli-Staudacher used the term "lean healthcare" for the first time in the paper: *Lean Healthcare. An experience in Italy* [113] published as a lean approach to the healthcare sector. The paper did not focus on service improvement but in how to reduce inventories of drugs and other healthcare supplies by implementing tools from lean logistics.

In 2009, Mark Graban published the book *Lean Hospitals* [114] as a practical guide for adapting lean tools in hospital management.

In 2011 [115], lean healthcare was proposed as a more holistic system for improving healthcare organizations and how to assess them.

In 2016 [116], Costa et al. presented a review based on six parameters: research method, country, healthcare area, implementation, lean tools and methods, and results.

In 2020, Santos et al. [117] highlighted new research areas for the future.

As a conclusion, lean healthcare/hospital is a transfer to services, targeted on healthcare services, and it includes hospital management. It applies lean principles and tools toward improving patient care. Interest in it was very limited until 2015, and it has seen moderate growth in the last 3 years as new research proposals are put forth (Figure 17).

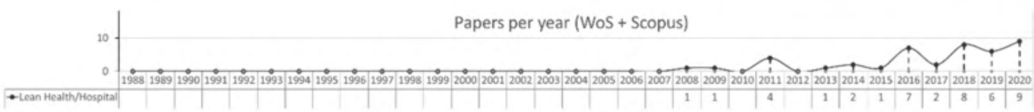


Figure 17. Lean healthcare/hospital evolution.

3.2.14. Lean Startup (2011)

The first reference to the term "lean startup" in the research literature was by Blank in 2013, in *Why the Lean Start-up Changes Everything* [118]. The author expanded on the concept proposed by Ries in his 2011 book *The Lean Startup* [119], proposing it as a new methodology for launching companies faster and cheaper than the methods of a traditional business plan. As a consequence, the term can be considered a variation that applies lean principles to the launching of new businesses.

In 2017, Frederiksen et al. [120] presented evidence from the scientific literature for their in-depth look at the methodological proposals in Ries's book.

In 2018, Bortolini et al. [121] clarified how the foundations of lean startup are linked with lean manufacturing: maximizing customer value while minimizing waste.

In 2020, Silva et al. [122] provided new perspectives on developing a business model and discussed complementary methodologies, such as agile methodologies and customer development.

As a conclusion, lean startup is a transfer to launching a new business. It uses lean principles to launch new business models while reducing time-to-market and minimizing initial investment and risks. Since its appearance in 2011, interest in the topic has seen sustained growth (Figure 18).

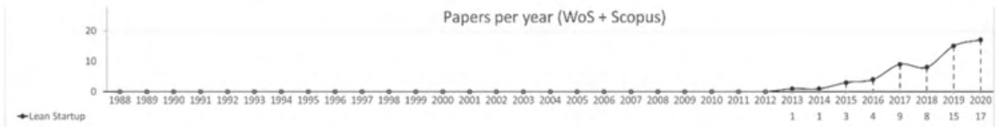


Figure 18. Lean startup evolution.

3.2.15. Lean 4.0 (2017)

Lean 4.0 (L4.0) is the most recent specifier. It was introduced in 2017 by Metternich et al. [123] in the German language paper *Lean 4.0—Between Contradiction and Vision*, which combined lean with Industry 4.0 (I4.0). The authors reflect on the compatibility between lean philosophy and technologies under the umbrella of I4.0, concluding that lean appears to be a prerequisite for digitization.

In 2018, Mayr et al. [124] agreed that lean enabled the successful introduction of I4.0 and concluded that both views complement each other. They present a detailed overview on how the most relevant lean tools can be complemented with I4.0 technologies.

In 2020, Valamede et al. [125] went further by taking a holistic view to identify 25 synergy points between lean tools and 4.0 technologies. Perico et al. [126] proposed new perspectives on how to incorporate artificial intelligence to support human decisions in key lean 4.0 topics (production control, maintaining continuous pull flow, and early prediction of machine failure). Under the denomination "lean Industry 4.0", Ejsmont et al. [127] identified the research trends combining "lean management" and I4.0. to go further in reducing waste to achieve a new level of operational excellence.

At the present moment, only four papers have been found with "lean 4.0" in the title, although increasing interest (see Figure 19) is being generated in the relationships between Industry 4.0 and different lean aspects: lean production [49,128], lean manufacturing [54,129], lean and green [85,130], lean construction [74], lean enterprise [70], lean healthcare [131], lean management [132], lean six sigma [133], lean supply chain [64], and lean thinking [86].

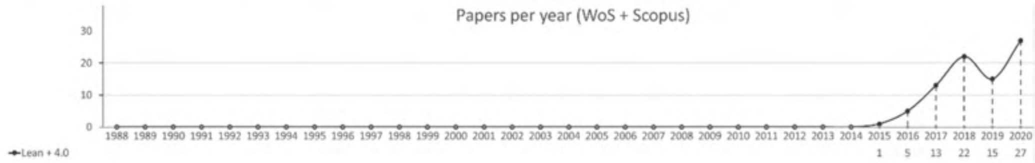


Figure 19. Papers about relationships between lean and Industry 4.0.

In total, 83 papers have been identified linking "lean" and I4.0. An analysis based on the address of the corresponding author shows countries leading the research in this topic: Germany is in the first position as the term "Industry 4.0" was coined in Germany. Nevertheless, an arising interest is shown in different nations, particularly in Brazil, Portugal and Italy (see Figure 20).

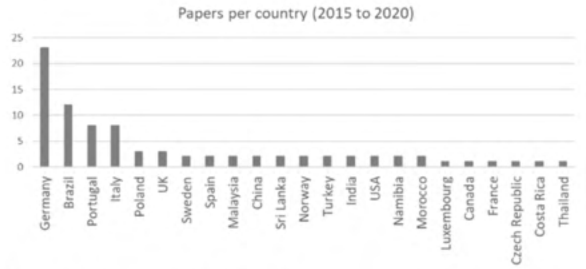


Figure 20. Papers linking lean and Industry 4.0 by corresponding author's country (2015–2020).

As a conclusion, lean 4.0 is a combination of lean manufacturing (or lean production) principles and tools with Industry 4.0 technologies. It deals with the synergies and complementarity of I4.0 with lean with the intention of reducing waste and complexity. It appears to be a promising field of research in the coming years.

4. Conclusions

This article explores the origins and diversification of the term "lean" as a management concept, in both the manufacturing and service sectors. It takes a historical perspective in answering three research questions. To achieve this, 4.962 indexed records and 20 seminal books were analyzed by following a systematic literature review methodology.

Our research questions can be answered as follows:

About the historical origin of the term "lean": it was created in 1988 as "lean production system", a generic denomination for the Toyota production system. The best-selling book, *The Machine that Changed the World* (1990), populated the term "lean production" by absorbing other alternative expressions that existed at that time.

The previously used terms (which had similar intentions of denominating the Toyota production system without naming Toyota) were: *Japanese manufacturing techniques, stockless production, JIT production, value-added production, continuous improvement manufacturing, non-stock production*, and *fragile production*.

Since 1990, the term lean has evolved over time. Its evolution and diversification can be explained through four mechanisms (combined over time): expansion, transfer, targeting, and combination. This resulted in the creation of a confusing puzzle of lean specifier.

This paper has outlined the paths of evolution by using the most cited specifiers in the academic literature:

- Between 1990 and 2000, the term lean remained mainly in its original field of operations management, with the following specifiers: lean production, lean manufacturing, lean logistics, lean supply chain, lean product, lean construction, and lean and green. The first attempt to upgrade the concept to a more conceptual level was greeted with initially limited academic interest: lean management, lean enterprise, and lean thinking.

- In 2000, the combined term "lean six sigma" emerged and up to the present has received much attention in both the manufacturing and service sectors.
- Since 2006, the term "lean" was progressively applied in the service field with new specifiers: lean service, lean hospital, lean healthcare, lean office, lean startup.
- The last specifier, lean 4.0., was created in 2017 as a synergetic combination between lean manufacturing (or lean production) and the Industry 4.0 paradigm. At the moment, it focuses only on the manufacturing field.

The term "lean", as a management concept that allows organizations to remain competitive by removing waste from their processes, has been fully adopted by management researchers. Based on a bibliometric analysis of published papers-per-year, we can say that research interest in this topic has grown exponentially since 1988.

This paper reveals some implications for future research: The use of lean perspective can be further extended beyond its current development, adapting its principles and tools to different sectors or applications. The diversification mechanisms described above can open new research areas in a fast-changing, complex and competitive world. The lean approach combined with the new emerging disruptive technologies (so-called Industry 4.0) open new avenues for future research as intelligent construction, sustainability, smart cities, environmental improvement or public governance.

Author Contributions: Conceptualization, F.G.-V.; methodology, F.G.-V. and A.S.; formal analysis, J.A.Y.-F.; investigation, F.G.-V.; data curation, F.G.-V.; writing—original draft preparation, F.G.-V.; writing—review and editing, A.S.; supervision, J.A.Y.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was funded by the DGA-FSE (Diputación General de Aragón—Fondo Social Europeo) project T56_20R: Grupo de Ingeniería de Fabricación y Metrología Avanzada.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jasti, N.V.K.; Kodali, R. Lean production: Literature review and trends. *Int. J. Prod. Res.* **2014**, *53*, 867–885. [CrossRef]
2. Moyano-Fuentes, J.; Sacristán-Díaz, M. Learning on lean: A review of thinking and research. *Int. J. Oper. Prod. Manag.* **2012**, *32*, 551–582. [CrossRef]
3. Psomas, E.; Antony, J. Research gaps in Lean manufacturing: A systematic literature review. *Int. J. Qual. Reliab. Manag.* **2019**, *36*, 815–839. [CrossRef]
4. Antony, J.; Psomas, E.; Garza-Reyes, J.A.; Hines, P. Practical implications and future research agenda of lean manufacturing: A systematic literature review. *Prod. Plan. Control.* **2020**, *32*, 889–925. [CrossRef]
5. Bhamu, J.; Sangwan, K.S. Lean manufacturing: Literature review and research issues. *Int. J. Oper. Prod. Manag.* **2014**, *34*, 876–940. [CrossRef]
6. Shah, R.; Ward, P.T. Defining and developing measures of lean production. *J. Oper. Manag.* **2007**, *25*, 785–805. [CrossRef]
7. Schonberger, R.J.; Schonberger, R.J. The disintegration of lean manufacturing and lean management. *Bus. Horizons* **2019**, *62*, 359–371. [CrossRef]
8. Giroux, H. 'It Was Such a Handy Term': Management Fashions and Pragmatic Ambiguity. *J. Manag. Stud.* **2006**, *43*, 1227–1260. [CrossRef]
9. Dorval, M.; Jobin, M.-H.; Benomar, N. Lean culture: A comprehensive systematic literature review. *Int. J. Prod. Perform. Manag.* **2019**, *68*, 920–937. [CrossRef]
10. Templier, M.; Paré, G. A Framework for Guiding and Evaluating Literature Reviews. *Commun. Assoc. Inf. Syst.* **2015**, *37*, 6. [CrossRef]
11. Tranfield, D.; Denyer, D.; Smart, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]
12. Denyer, D.; Tranfield, D. Producing a Systematic Review. In *The SAGE Handbook of Organizational Research Methods*; SAGE: Thousand Oaks, CA, USA, 2009.
13. Ciano, M.P.; Pozzi, R.; Rossi, T.; Strozzi, F. How IJPR has addressed 'lean': A literature review using bibliometric tools. *Int. J. Prod. Res.* **2019**, *57*, 5284–5317. [CrossRef]
14. Danese, P.; Manfè, V.; Romano, P. A Systematic Literature Review on Recent Lean Research: State-of-the-art and Future Directions. *Int. J. Manag. Rev.* **2017**, *20*, 579–605. [CrossRef]

15. Soliman, M.; Saurin, T. Lean production in complex socio-technical systems: A systematic literature review. *J. Manuf. Syst.* **2017**, *45*, 135–148. [CrossRef]
16. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
17. Sinha, N.; Matharu, M. A comprehensive insight into Lean management: Literature review and trends. *J. Ind. Eng. Manag.* **2019**, *12*, 302–317. [CrossRef]
18. Hines, P.; Holweg, M.; Rich, N. Learning to evolve. *Int. J. Oper. Prod. Manag.* **2004**, *24*, 994–1011. [CrossRef]
19. Holweg, M. The genealogy of lean production. *J. Oper. Manag.* **2006**, *25*, 420–437. [CrossRef]
20. Sayles, L.R. Managerial Productivity: Who Is Fat and What Is Lean? *Interfaces* **1985**, *15*, 54–59. [CrossRef]
21. Havn, E.; Womack, J.P.; Jones, D.T.; Ross, D. *The Machine that Changed the World*; Rawson Associates: New York, NY, USA, 1990.
22. New, S.J. Celebrating the enigma: The continuing puzzle of the Toyota Production System. *Int. J. Prod. Res.* **2007**, *45*, 3545–3554. [CrossRef]
23. Krafcik, J.F. Triumph of the lean production system. *Sloan Manag. Rev.* **1988**, *30*, 41–52.
24. Shimada, H.; MacDuffie, J.P. *Industrial Relations and 'Humanware*; Working Paper; Sloan School of Management: Cambridge, MA, USA, 1986.
25. Sugimori, Y.; Kusunoki, K.; Cho, F.; Uchikawa, S. Toyota production system and Kanban system Materialization of just-in-time and respect-for-human system. *Int. J. Prod. Res.* **1977**, *15*, 553–564. [CrossRef]
26. Ohno, T.I. *Toyota Seisan Hoshiki: Datsu-Kibo no Keiei o Mezashite*; DiamondYsha: Tokyo, Japan, 1978.
27. Ohno, T. How the Toyota Production System was Created. *Jpn. Econ. Stud.* **1982**, *10*, 83–101. [CrossRef]
28. Sato, K.; Hoshino, Y. *The Anatomy of Japanase Business*; M.E. Sharpe Inc.: Armonk, NY, USA, 1984.
29. Shingo, S.; Dillon, A.P. *A Study of the Toyota Production System: From an Industrial Engineering Viewpoint (Produce What Is Needed, When It's Needed)*; CRC Press: Boca Raton, FL, USA, 1898.
30. Monden, Y. *Toyota Production System: Practical Approach to Production Management*; Industrial Engineering and Management Press, Institute of Industrial Engineers: Atlanta, GA, USA, 1983.
31. Schonberger, R.J. *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*; The Free Press: New York, NY, USA, 1982.
32. Hall, R.W. *Zero Inventory*; Dow Jones-Irwin Professional Pub: Homewood, IL, USA, 1983.
33. Hall, R.W.; Hall, J. *Attaining Manufacturing Excellence: Just-in-Time, Total Quality, Total People Involvement*; Dow Jones-Irwin Professional Pub: Homewood, IL, USA, 1987.
34. Cusumano, M.A. *The Japanese Automobile Industry: Technology and Management at Nissan and Toyota. Council on East Asian Studies*; Harvard University Press: Cambridge, MA, USA, 1985.
35. Shingō, S. *A Revolution in Manufacturing: The SMED System*; Productivity Press: New York, NY, USA, 1985.
36. Japan Management Association. *Kanban Just-in Time at Toyota: Management Begins at the Workplace*; Productivity Press: New York, NY, USA, 1986.
37. Imai, M. *Kaizen (Ky'zen): The Key to Japan's Competitive Success*; Random Housre Business Division: New York, NY, USA, 1986.
38. Nakajima, S. *Introduction to TPM: Total Productive Maintenance*; Productivity Press: New York, NY, USA, 1988.
39. Ohno, T. *Toyota Production System: Beyond Large-Scale Production*; Productivity Press: New York, NY, USA, 1988.
40. Williams, K.; Haslam, C.; Williams, J.; Cultler, T.; Adcroft, A.; Johal, S. Against lean production. *Econ. Soc.* **1992**, *21*, 321–354. [CrossRef]
41. Berggren, C. Lean Production—The End of History? *Work. Employ. Soc.* **1993**, *7*, 163–188. [CrossRef]
42. Cusumano, M. The limits of "Lean". *Sloan Manag. Rev.* **1994**, *35*, 4.
43. Delbridge, R.; Oliver, N. Narrowing the gap? Stock turns in the Japanese and Western car industries. *Int. J. Prod. Res.* **1991**, *29*, 2083–2095. [CrossRef]
44. Womack, J.P.; Jones, D.T. From lean production to the lean enterprise. *IEEE Eng. Manag. Rev.* **1996**, *24*, 4.
45. Womack, J.P.; Jones, D.T. *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*; Simon & Schuster: New York, NY, USA, 1996.
46. Bicheno, J. *The Lean Toolbox*; PICSIE Books: Buckingham, UK, 1998.
47. Marodin, G.A.; Saurin, T. Implementing lean production systems: Research areas and opportunities for future studies. *Int. J. Prod. Res.* **2013**, *51*, 6663–6680. [CrossRef]
48. Hai, H.; Wenxing, L. The Analysis of Industry 4.0 and Lean Production. In Proceedings of the Second International Symposium-Management, Innovation and Development, Guangzhou, China, 1 December 2015.
49. Rossini, M.; Costa, F.; Tortorella, G.; Portioli-Staudacher, A. The interrelation between Industry 4.0 and lean production: An empirical study on European manufacturers. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 3963–3976. [CrossRef]
50. Ciano, M.P.; Dallasega, P.; Orzes, G.; Rossi, T. One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: A multiple case study. *Int. J. Prod. Res.* **2020**, *59*, 1386–1410. [CrossRef]
51. Powell, C. Lean Manufacturing Organization, 21st Century. In Proceedings of the Annual International Conference Proceedings-American Production and Inventory Control Society, 1 November 1993; Available online: https://www.amazon.com/International-Conference-Proceedings-INTERNATIONAL-PROCEEDINGS/dp/1558221042 (accessed on 28 October 2021).

52. Shah, R.; Ward, P.T. Lean manufacturing: Context, practice bundles, and performance. *J. Oper. Manag.* **2002**, *21*, 129–149. [CrossRef]
53. Jasti, N.V.K.; Kodali, R. A literature review of empirical research methodology in lean manufacturing. *Int. J. Oper. Prod. Manag.* **2014**, *34*, 1080–1122. [CrossRef]
54. Sanders, A.; Elangeswaran, C.; Wulfsberg, J. Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. *J. Ind. Eng. Manag.* **2016**, *9*, 811–833. [CrossRef]
55. Valamede, L.S.; Akkari, A.C.S. Lean Manufacturing and Industry 4.0: A Holistic Integration Perspective in the Industrial Context. 2020, pp. 63–68. Available online: https://ieeexplore.ieee.org/abstract/document/9080393 (accessed on 28 October 2021).
56. Fynes, B.; Ennis, S. From lean production to lean logistics: The case of microsoft Ireland. *Eur. Manag. J.* **1994**, *12*, 322–331. [CrossRef]
57. Lamming, R. Squaring lean supply with supply chain management. *Int. J. Oper. Prod. Manag.* **1996**, *16*, 183–196. [CrossRef]
58. Huallacháin, B.; Wasserman, D. Vertical Integration in a Lean Supply Chain: Brazilian Automobile Component Parts*. *Econ. Geogr.* **2008**, *75*, 21–42. [CrossRef]
59. Perez, C.; De Castro, R.; Simons, D.; Gimenez, G. Development of lean supply chains: A case study of the Catalan pork sector. *Supply Chain Manag. Int. J.* **2010**, *15*, 55–68. [CrossRef]
60. Garcia-Buendia, N.; Moyano-Fuentes, J.; Maqueira-Marín, J.M.; Cobo, M.J. 22 Years of Lean Supply Chain Management: A science mapping-based bibliometric analysis. *Int. J. Prod. Res.* **2020**, *59*, 1901–1921. [CrossRef]
61. Tortorella, G.L.; Miorando, R.F.; Fries, C.E.; Vergara, A.M.C. On the relationship between Lean Supply Chain Management and performance improvement by adopting Industry 4.0 technologies. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Paris, France, 26–27 July 2018.
62. Tortorella, G. Erratum. *Supply Chain Manag. Int. J.* **2019**, *24*, 301. [CrossRef]
63. Núñez-Merino, M.; Maqueira-Marín, J.M.; Moyano-Fuentes, J.; Martínez-Jurado, P.J. Information and digital technologies of Industry 4.0 and Lean supply chain management: A systematic literature review. *Int. J. Prod. Res.* **2020**, *58*, 5034–5061. [CrossRef]
64. Jones, D.T.; Hines, P.; Rich, N. Lean logistics. *Int. J. Phys. Distrib. Logist. Manag.* **1997**, *27*, 153–173. [CrossRef]
65. Petrovic, O.; Zsifkovits, H.E. Business process re-engineering as an enabling factor for lean management. In Proceedings of the IFIP TC8 Open Conference on Business Process Re-engineering: Information Systems Opportunities and Challenges, Queensland Gold Coast, Australia, 8–11 May 1994.
66. Martínez-Jurado, P.J.; Moyano-Fuentes, J. Lean Management, Supply Chain Management and Sustainability: A Literature Review. *J. Clean. Prod.* **2014**, *85*, 134–150. [CrossRef]
67. Martinez, F.; Jirsak, P.; Lorenc, M. Industry 4.0. the End Lean Management? In *The 10th International Days of Statistics and Economics*; Melandrium: Prague, Czech Republic, 2016; pp. 1189–1197.
68. Jasti, N.V.K.; Kota, S.; Kale, S.R. Development of a framework for lean enterprise. *Meas. Bus. Excel.* **2020**, *24*, 431–459. [CrossRef]
69. Dombrowski, U.; Wullbrandt, J.; Fochler, S. Center of Excellence for Lean Enterprise 4.0. *Procedia Manuf.* **2019**, *31*, 66–71. [CrossRef]
70. Koskela, L. Lean production in lean construction. In Proceedings of the National Construction and Management Conference, Sydney, Australia, 17–18 February 1994.
71. Thomas, H.R.; Horman, M.J.; De Souza, U.E.L.; Završki, I. Reducing Variability to Improve Performance as a Lean Construction Principle. *J. Constr. Eng. Manag.* **2002**, *128*, 144–154. [CrossRef]
72. Salem, O.; Solomon, J.; Genaidy, A.; Minkarah, I. Lean Construction: From Theory to Implementation. *J. Manag. Eng.* **2006**, *22*, 168–175. [CrossRef]
73. Koskela, L.; Ferrantelli, A.; Niiranen, J.; Pikas, E.; Dave, B. Epistemological Explanation of Lean Construction. *J. Constr. Eng. Manag.* **2019**, *145*, 04018131. [CrossRef]
74. Lekan, A.; Clinton, A.; Fayomi, O.S.I.; James, O. Lean Thinking and Industrial 4.0 Approach to Achieving Construction 4.0 for Industrialization and Technological Development. *Buildings* **2020**, *10*, 221. [CrossRef]
75. Mano, A.P.; Da Costa, S.E.G.; De Lima, E.P. Criticality assessment of the barriers to Lean Construction. *Int. J. Prod. Perform. Manag.* **2020**, *70*, 65–86. [CrossRef]
76. Florida, R. Lean and Green: The Move to Environmentally Conscious Manufacturing. *Calif. Manag. Rev.* **1996**, *39*, 80–105. [CrossRef]
77. King, A.A.; Lenox, M.J. Lean and green? An empirical examination of the relationship between lean production and environmental performance. *Prod. Oper. Manag.* **2009**, *10*, 244–256. [CrossRef]
78. Kainuma, Y.; Tawara, N. A multiple attribute utility theory approach to lean and green supply chain management. *Int. J. Prod. Econ.* **2006**, *101*, 99–108. [CrossRef]
79. Garza-Reyes, J.A. Lean and green—A systematic review of the state-of-the-art literature. *J. Clean. Prod.* **2015**, *102*, 18–29. [CrossRef]
80. Farias, L.M.S.; Santos, L.C.; Gohr, C.F.; de Oliveira, L.C.; Amorim, M.H.D.S. Criteria and practices for lean and green performance assessment: Systematic review and conceptual framework. *J. Clean. Prod.* **2019**, *218*, 746–762. [CrossRef]
81. Farias, L.M.S.; Santos, L.C.; Gohr, C.F.; Rocha, L.O. An ANP-based approach for lean and green performance assessment. *Resour. Conserv. Recycl.* **2018**, *143*, 77–89. [CrossRef]
82. Moro, S.R.; Cauchick-Miguel, P.A.; Campos, L.M.S. Product-service systems towards eco-effective production patterns: A Lean-Green design approach from a literature review. *Total. Qual. Manag. Bus. Excel.* **2019**, *32*, 1046–1064. [CrossRef]

83. Duarte, S.; Cabrita, M.D.R.; Cruz-Machado, V. Business Model, Lean and Green Management and Industry 4.0: A Conceptual Relationship. *Adv. Intell. Syst. Comput.* **2019**, *1*, 359–372. [CrossRef]
84. Leong, W.D.; Teng, S.Y.; How, B.S.; Ngan, S.L.; Rahman, A.A.; Tan, C.P.; Ponnambalam, S.; Lam, H.L. Enhancing the adaptability: Lean and green strategy towards the Industry Revolution 4.0. *J. Clean. Prod.* **2020**, *273*, 122870. [CrossRef]
85. Piercy, N.F.; Morgan, N.A. The impact of lean thinking and the lean enterprise on marketing: Threat or synergy? *J. Mark. Manag.* **1997**, *13*, 679–693. [CrossRef]
86. Bittencourt, V.L.; Alves, A.; Leão, C.P. Industry 4.0 triggered by Lean Thinking: Insights from a systematic literature review. *Int. J. Prod. Res.* **2020**, *59*, 1496–1510. [CrossRef]
87. Karlsson, C.; Ahlstrom, P. The difficult path to lean product development. *J. Prod. Innov. Manag.* **1996**, *13*, 283–295. [CrossRef]
88. León, H.C.M.; Farris, J.A. Lean Product Development Research: Current State and Future Directions. *Eng. Manag. J.* **2011**, *23*, 29–51. [CrossRef]
89. Liker, J.K.; Morgan, J.M. The Toyota Way in Services: The Case of Lean Product Development. *Acad. Manag. Perspect.* **2006**, *20*, 5–20. [CrossRef]
90. Sassanelli, C.; Pezzotta, G.; Rossi, M.; Terzi, S.; Cavalieri, S. Towards a Lean Product Service Systems (PSS) Design: State of the Art, Opportunities and Challenges. *Procedia CIRP* **2015**, *30*, 191–196. [CrossRef]
91. Sassanelli, C.; Rossi, M.; Pezzotta, G.; Pacheco, D.; Terzi, S. Defining lean product service systems features and research trends through a systematic literature review. *Int. J. Prod. Lifecycle Manag.* **2019**, *12*. [CrossRef]
92. Bowen, D.E.; Youngdahl, W.E. "Lean" service: In defense of a production-line approach. *Int. J. Serv. Ind. Manag.* **1998**, *9*, 207–225. [CrossRef]
93. Swank, C.K. The lean service machine. *Harv. Bus. Rev.* **2003**, *81*, 123.
94. Suárez-Barraza, M.F.; Smith, T.; Dahlgaard-Park, S.M. Lean Service: A literature analysis and classification. *Total. Qual. Manag. Bus. Excel.* **2012**, *23*, 359–380. [CrossRef]
95. Sprigg, C.A.; Jackson, P.R. Call centers as lean service environments: Job-related strain and the mediating role of work design. *J. Occup. Heal. Psychol.* **2006**, *11*, 197–212. [CrossRef] [PubMed]
96. Piercy, N.; Rich, N. High quality and low cost: The lean service centre. *Eur. J. Mark.* **2009**, *43*, 1477–1497. [CrossRef]
97. LaGanga, L.R. Lean service operations: Reflections and new directions for capacity expansion in outpatient clinics. *J. Oper. Manag.* **2010**, *29*, 422–433. [CrossRef]
98. Gupta, S.; Sharma, M. Lean services: A systematic review. *Int. J. Prod. Perform. Manag.* **2016**, *65*, 1025–1056. [CrossRef]
99. Sheridan, J.H. "Lean Sigma" Synergy. *Ind. Week* **2000**, *249*, 17.
100. Furterer, S.; Elshennawy, A.K. Implementation of TQM and lean Six Sigma tools in local government: A framework and a case study. *Total. Qual. Manag. Bus. Excel.* **2005**, *16*, 1179–1191. [CrossRef]
101. Wheat, B.; Mills, C.; Carnell, M. *Leaning into Six Sigma: A Parable of the Journey to Six Sigma and a Lean Enterprise*; McGraw Hill Professional: New York, NY, USA, 2003.
102. Kumar, M.; Antony, J.; Singh, R.; Tiwari, M.K.; Perry, D. Implementing the Lean Sigma framework in an Indian SME: A case study. *Prod. Plan. Control.* **2006**, *17*, 407–423. [CrossRef]
103. Albliwi, S.A.; Antony, J.; Lim, S.A.H. A systematic review of Lean Six Sigma for the manufacturing industry. *Bus. Process. Manag. J.* **2015**, *21*, 665–691. [CrossRef]
104. Rosa, A.C.M.; Broday, E.E. Comparative analysis between the industrial and service sectors: A literature review of the improvements obtained through the application of lean six sigma. *Int. J. Qual. Res.* **2018**, *12*, 1. [CrossRef]
105. Sony, M. Design of cyber physical system architecture for industry 4.0 through lean six sigma: Conceptual foundations and research issues. *Prod. Manuf. Res.* **2020**, *8*, 158–181. [CrossRef]
106. Chiarini, A.; Kumar, M. Lean Six Sigma and Industry 4.0 integration for Operational Excellence: Evidence from Italian manufacturing companies. *Prod. Plan. Control.* **2020**, *32*, 1084–1101. [CrossRef]
107. Productivity Press Development Team. *The Lean Office, Collected Practices & Cases*; Productivity Press: New York, NY, USA, 2005.
108. Locher, D. *Lean Office and Service Simplified: The Definitive How-To Guide*; Taylor & Francis: Abingdon, UK, 2011.
109. Herkommer, J.; Herkommer, O. Lean Office-System. *Z. Wirtsch. Fabr.* **2006**, *101*, 378–381. [CrossRef]
110. Nieuwenhuis, M.; Knight, C.; Postmes, T.; Haslam, S.A. The relative benefits of green versus lean office space: Three field experiments. *J. Exp. Psychol. Appl.* **2014**, *20*, 199–214. [CrossRef]
111. Freitas, R.D.C.; Freitas, M.D.C.D. Information management in lean office deployment contexts. *Int. J. Lean Six Sigma* **2020**, *11*, 1161–1192. [CrossRef]
112. Yokoyama, T.T.; DE Oliveira, M.A.; Futami, A.H. A Systematic Literature Review on Lean Office. *Ind. Eng. Manag. Syst.* **2019**, *18*, 67–77. [CrossRef]
113. Portioli-Staudacher, A. *Lean Healthcare. An Experience in Italy*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 485–492. [CrossRef]
114. Graban, M. *Lean Hospitals: Improving Quality, Patient Safety, and Employee Engagement*; CCR Press, Taylor & Francis Group: New York, NY, USA, 2009.
115. Dahlgaard, J.J.; Pettersen, J.; Dahlgaard-Park, S.M. Quality and lean health care: A system for assessing and improving the health of healthcare organisations. *Total. Qual. Manag. Bus. Excel.* **2011**, *22*, 673–689. [CrossRef]

116. Costa, L.B.M.; Filho, M.G. Lean healthcare: Review, classification and analysis of literature. *Prod. Plan. Control.* **2016**, *27*, 823–836. [CrossRef]
117. Santos, A.C.D.S.G.D.; Reis, A.; De Souza, C.G.; Dos Santos, I.L.; Ferreira, L.A.F. The first evidence about conceptual vs analytical lean healthcare research studies. *J. Heal. Organ. Manag.* **2020**, *34*, 789–806. [CrossRef]
118. Blank, S. Why the lean start-up changes everything. *Harv. Bus. Rev.* **2013**, *91*, 5.
119. Ries, E. *The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses*; Crown Business: New York, NY, USA, 2011.
120. Frederiksen, D.L.; Brem, A. How do entrepreneurs think they create value? A scientific reflection of Eric Ries' Lean Startup approach. *Int. Entrep. Manag. J.* **2016**, *13*, 169–189. [CrossRef]
121. Bortolini, R.F.; Cortimiglia, M.N.; Danilevicz, A.D.M.F.; Ghezzi, A. Lean Startup: A comprehensive historical review. *Manag. Decis.* **2018**, *59*, 1765–1783. [CrossRef]
122. Silva, D.S.; Ghezzi, A.; de Aguiar, R.B.; Cortimiglia, M.N.; Caten, C.S.T. Lean Startup, Agile Methodologies and Customer Development for business model innovation. *Int. J. Entrep. Behav. Res.* **2019**, *26*, 595–628. [CrossRef]
123. Metternich, J.; Müller, M.; Meudt, T.; Schaede, C. Lean 4.0—Zwischen Widerspruch und Vision. *ZWF* **2017**, *112*, 346–348. [CrossRef]
124. Mayr, A.; Weigelt, M.; Kühl, A.; Grimm, S.; Erll, A.; Potzel, M.; Franke, J. Lean 4.0—A conceptual conjunction of lean management and Industry 4.0. *Procedia CIRP* **2018**, *72*, 622–628. [CrossRef]
125. Valamede, L.S.; Akkari, A.C.S. Lean 4.0: A New Holistic Approach for the Integration of Lean Manufacturing Tools and Digital Technologies. *Int. J. Math. Eng. Manag. Sci.* **2020**, *5*, 851–868. [CrossRef]
126. Perico, P.; Mattioli, J. Empowering Process and Control in Lean 4.0 with Artificial Intelligence. In Proceedings of the 3rd International Conference on Artificial Intelligence for Industries (AI4I), Irvine, CA, USA, 21–23 September 2020; pp. 6–9. [CrossRef]
127. Ejsmont, K.; Gladysz, B.; Corti, D.; Castaño, F.; Mohammed, W.M.; Lastra, J.L.M. Towards "Lean Industry 4.0"—Current trends and future perspectives. *Cogent Bus. Manag.* **2020**, *7*, 1781995. [CrossRef]
128. Wagner, T.A.; Herrmann, C.; Thiede, S. Industry 4.0 Impacts on Lean Production Systems. *Procedia CIRP* **2017**, *63*, 125–131. [CrossRef]
129. Buer, S.-V.; Strandhagen, J.O.; Chan, F.T.S. The link between Industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda. *Int. J. Prod. Res.* **2018**, *56*, 2924–2940. [CrossRef]
130. Duarte, S.; Cruz-Machado, V. An investigation of lean and green supply chain in the Industry 4.0. In Proceedings of the 2017 International Symposium on Industrial Engineering and Operations Management (IEOM), Rabat, Morocco, 11–13 April 2017.
131. Ilangakoon, T.; Weerabahu, S.; Wickramarachchi, R. Combining Industry 4.0 with Lean Healthcare to Optimize Operational Performance of Sri Lankan Healthcare Industry. In Proceedings of the International Conference on Production and Operations Management Society (POMS), Peradeniya, Sri Lanka, 14–16 December 2018; pp. 1–8. [CrossRef]
132. Sony, M. Industry 4.0 and lean management: A proposed integration model and research propositions. *Prod. Manuf. Res.* **2017**, *6*, 416–432. [CrossRef]
133. Yadav, N.; Shankar, R.; Singh, S.P. Impact of Industry4.0/ICTs, Lean Six Sigma and quality management systems on organisational performance. *TQM J.* **2020**, *32*, 815–835. [CrossRef]

2.2. Person-based design: A human-centered approach for lean factory design.

Constatada la diversificación del término "lean" a diferentes ámbitos fuera del mundo de las operaciones industriales y su diversificación conceptual, este artículo tiene como objetivo presentar "lean" en el entorno industrial y, particularmente como un Sistema de Producción tal y como fue descrito en sus orígenes.

Para ello se propone un marco conceptual sencillo para un Sistema socio-técnico genérico como un conjunto de elementos (principios, herramientas, métodos y personas) que, interrelacionados ordenadamente entre sí, contribuyen a un objetivo común. Se introduce después como caso particular un Sistema de Producción Lean cuyo objetivo es la competitividad de la planta productiva.

Recuperando el principio seminal "*respect-for-human*" se presenta el Método "Diseño desde la persona" (*Person-Based Design*), uno de los hilos conductores de esta tesis.

Para terminar, y a modo ilustrativo, se desarrolla un caso de estudio real proveniente de la práctica profesional del autor para la aplicación del Método "Diseño desde la persona" y los resultados obtenidos.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 41 (2019) 445–452

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

8th Manufacturing Engineering Society International Conference

Person-Based Design: A Human-Centered Approach for Lean Factory Design

Francisco Gil Vilda[a,]*, José Antonio Yagüe Fabra[b], Albert Sunyer Torrents[c]

[a]LEANBOX SL. Sardenya 174, 5º, 4ª 08013, Barcelona, Spain
[b]I3A-Universidad de Zaragoza, C/ María de Luna, 3, Zaragoza 50018, Spain
[c]ESEIAAT, Universidad Politécnica de Catalunya, C. Colom, 11, 08222, Terrassa, Spain

Abstract

In a highly competitive and changing industrial environment, an organizational system that remains permanently aligned with the market is becoming a competitiveness factor. Consequently, industrial organizations face the challenge of building effective production systems that integrate the development of people, thus improving their capacities and skills for solving complex problems while respecting their needs and aspirations as individuals. This challenge is particularly relevant when intensive handwork is needed and, consequently, high pressure on labor (and space) productivity constitutes the main cost drivers. This paper proposes a method to design lean factories, thus fostering high productivity rates and respect-for-human.
A holistic model for a system is developed as an integrated set of Principles, Tools and Methods in constant interaction with people. A specific human-centered method (Person-Based Design) is proposed to guide an effective lean factory design in a real industrial setting. The Person-Based Design method defines seven layers of sequential design starting by the central layer "respect for people" and progressing outward into broader layers which include packaging, tools, value flow, layout and supply flows. The presented method is then implemented in a real industrial context and compared with an existing design.
The outcomes of this research provide a coherent mindset for managers facing an organizational change, and our structured method allows for the design of effective lean factories, which are particularly useful when space and/or labor productivity constitute the main factors of a firm's competitiveness.

Keywords: Lean Production Systems; Respect-for-people; Lean Manufacturing; Lean priciples, tools and methods

* Corresponding author. Tel.: +34 638 05 17 47.
E-mail address: francisco.gil.vilda@leanbox.es

© 2019 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of the 8th Manufacturing Engineering Society International Conference.

1. Introduction and literature review.

In the last decade, global markets have been becoming more and more competitive as they change at increasingly faster rates. As a consequence, industrial organizations are suffering from growing pressure due to shortening product-life-cycles, quality improvement, cost reduction, and the need to cut delivery times. This pressure is transmitted to their factories in the form of aggressive targets for raising productivity, improving quality excellence and shortening lead time.

Nowadays, having a production system adapted to this market dynamism, forms a key competitive factor for modern factories. Lean Production Systems (LPS) are particularly suitable in these contexts.

Lean Production is a generic name for the Toyota Production System (TPS), published for the first time in 1990 by Womack et al. [1]. TPS began development in a very practical way at Toyota from 1950 on, and it was fully documented by Taiichi Ohno (considered the father of TPS) [2] in a first English translation in 1978.

According to Holweg [3], the first English-language academic paper on TPS was published in 1977 [4]. This early article already introduces two central ideas for successfully implementing TPS:

- Systemic view. The production way developed by Toyota is considered a whole "system".
- *Respect-for-human* is considered one of TPS's *two major distinctive features* (together with Just-In-Time).

The literature shows that considering Lean to be a fragmented set of tools, rather than a whole system, forms one of the key factors for failure when implementing LPS [5,6]. Additionally, there is a general agreement about the importance of what some authors refer to as people involvement when facing necessary cultural changes [7]. The respect-for-human system has long been unrecognized, ignored or misunderstood by most senior managers outside Toyota, even though Ohno [2] and Monden [8] referred to it directly in their writings. Respect-for-human is a key antecedent of people involvement and active participation in process improvement [4].

Unfortunately, pressures on labor and space productivity usually involve a stressful and uncomfortable workplace. Additionally, cost reduction is too often interpreted purely as "job cutting". These factors create a paradox: Individuals perceive "active participation" as a firm's demand to deteriorate their workplace or, even worst, the previous step of losing their jobs, which goes against the respect-for-human system.

There is no simple answer to solve this paradox, which generates a high risk of failure when implementing LPS; however, industrial organizations should face the challenge to build effective production systems while developing people as well as respecting their needs and aspirations as individuals.

Interest is growing among firms who are seeking a holistic approach for designing Lean tools (see Carsten and al. [9]) and for Lean Production Systems (see de Kogel et al. [10]), yet a literature review finds neither a specific approach nor a specific method to mitigate this risk.

The aim of this study is to contribute to LPS understanding for manufacturing systems design. To do so, this paper develops a model of factory design from a human-centered approach and consistent with LPS principles. Figure 1 shows a visual summary of the paper's structure.

2. Lean Production as a socio-technical System.

Senge et al. [11] define a system as "a perceived whole whose elements hang together because they continually affect each other over time and operate toward a common purpose".

This paper proposes a specific model to describe a generic socio-technical system [12] as a set of elements (People, Principles, Tool and Methods) constantly interacting in order to achieve a certain objective (Fig 1a). This conceptualization is specified for Lean Production Systems below as a socio-technical system.

2.1. Set of a system elements.

- People: Individuals who perform their functions in permanent interaction with the Principles, Tools and Methods.
- Principles: Set of concepts which are considered valid and reliable: axioms, beliefs, dogmas, laws, etc. They shape the mindset of individuals. Principles shape "***how to think***".

- Tools: Elements to bring Principles into action. They are used by individuals and the community: a court, a ritual, a notation, a computer, etc. Tools establish "***how to do***".
- Methods: An orderly sequence in which tools are used to achieve a certain purpose. They establish the "***the order for doing***" or better: "***the right order for doing***".

2.2. Interactions between people, principles, methods and tools.

These four elements perpetually interact. The model postulates that the stability of the system is possible only if these interrelations are coherent. For this coherency, the following rules are proposed.

- Principles must be embedded in Tools and Methods. Tools and Methods must be complementary.
- People must feel integrated in the system and rewarded by it.

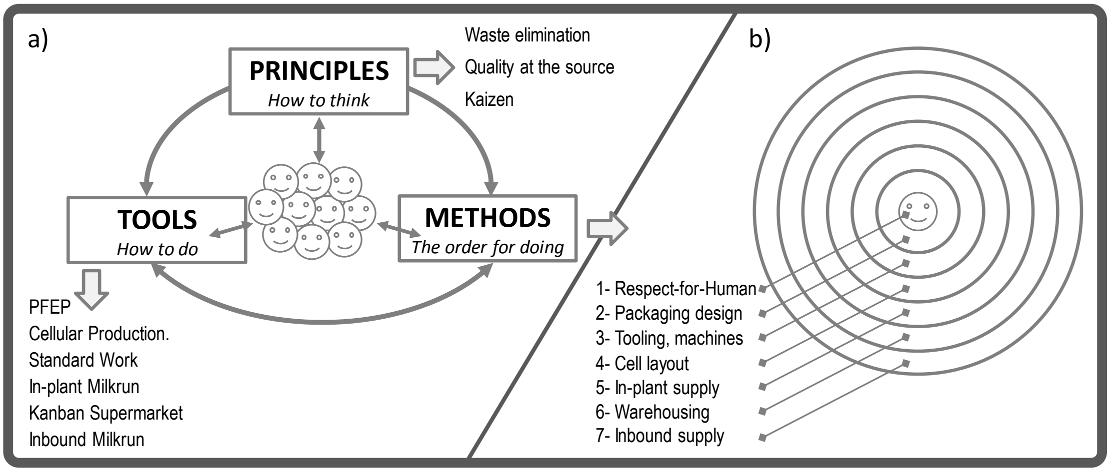


Fig. 1. Visual summary of the paper: (a) Lean as a system. (b) Person-Based Design method.

2.3. Lean Production System from a systemic perspective.

A Lean Production System could be defined as a social-technical system bounded to a human community (the factory) with the common objective of producing goods efficiently. A Lean Production System can be modeled as follows:

Lean Production Principles.

Different sets of principles have been proposed by different authors [13,14]. They can be reformulated in the following three principles:

- Reduce Waste (Muda). A customer obtains a product because he has needs. A product covers a customer´s need by doing what the customer expects and wants (functioning). In consequence, Added Value is defined as every process in the Value Chain which strictly adds functionality to the product. All the rest comprises waste to be eliminated or minimized.
- Quality at the Source. Every step in the process must supply just one quality part to the next step (which is considered its customer). The customer defines quality according to his needs.
- Continuous Improvement (Kaizen). Every person participates each time in waste elimination, with the collective objective of improving each process every day in search of operational excellence.

Lean Production Tools

Lean tools have been widely described in the literature (see, for example, [15]). The most relevant tools for the purposes of this paper are: Value Stream Mapping [16], 5S [17], Standard Work, U-Shaped Lines [18], Plan-For-Every-Part [19], In-plant Milkrun [20], Kanban Supermarket.

Lean Production Methods

An efficient Method should have Principles embedded, use Tools in the right order and ensure the *respect-for-people* through empowering people and active participation. Developing a detailed and repeatable Method that fits in any situation is difficult because of the wide range of variables involved: market, product, building, people skills, organizational culture, etc. Nevertheless, this paper proposes *Person-Based Design* (PBD) as a general Method for designing Lean Factories, particularly for manual or semi-automated processes. PBD has been induced from empirical Lean practice and it is implemented and discussed for a case study below.

3. Person-Based Design. An efficient Method for designing Lean Factories.

Person-Based Design is a human-centered method (Fig. 1b) that proposes a sequential process that begins with the person and progresses outward into broader design layers, following just one prioritization rule:

"The optimization of one layer must never have a negative impact on the efficiency of any of the inner layers."

Therefore, the design sequence can be described as follows.

3.1. Layer 1. Respect for people.

In manual or semi-automatic production processes, efficiency is based on people's skills and motivation. In this sense, the *respect-for-human* principle [4] requires the creation of a comfortable work space in the following ways:

- Minimizing motion waste.
- Optimizing ergonomics to focus human effort on adding value.

Involving workers in the design of the workspace is a key tool in this layer.

3.2. Layer 2. Packaging design.

Most of the workplace waste concerns the motions of picking up items and efforts to handle materials. To minimize this waste, parts must be placed close to the point of assembly and laid out in the right position to avoid risky motions and minimize variability. Additionally, the parts must be supplied with consideration toward the ergonomics of the materials-handling people.

This entails making containers as small and light as possible, easy-to-handle, and with parts arranged inside easy-to-pick.

Plan for Every Part [19] is the tool used to design the packaging.

3.3. Layer 3. Designing tools and machines.

The design of tools and machines must integrate the supply of parts in order to minimize, not only picking-up motions, but also operational motions and mental stress. Automation should support this objective by mitigating painful tasks in a better way than simply removing people from the process (see an example in [21]).

Standardized work and standardized workplace design are the tools for this layer.

3.4. Layer 4. Production line design.

Lean Production Systems seek continuous flow through "one-piece-flow" processes [18]. Workplaces must be arranged close to each other and laid out in accordance with the assembly process. This is the basis for the Cellular Manufacturing tool [22,18]. U-shaped production lines are widely preferred because they allow *shojinka* (adaptability) [8], but I-shaped lines can be used too (see [23] for a comparison between "I" and "U"). In any case, layout configuration must create a "working" area that is independent of the "supplying" area.

3.5. Layer 5. In-plant supply design.

Parts are delivered to the workplace in small amounts and in small containers, thus increasing the need for transportation and handling. In-plant supply design must minimize motion and ergonomic risks for people handling materials.

An in-plant Milkrun is the tool for this layer [20]. It consists of designing frequent, standardized and fixed-period loops to supply parts using multi-reference cart or train. The Milkrun stops are standardized, and containers must be arranged on the cart in a mirror configuration of the delivery points at the workplace.

3.6. Layer 6. Warehouse design.

After Milkrun cart are defined to minimize efforts supplying the production workplaces, the warehouse must be designed to minimize the motions required for loading the carts. Containers must be placed in a "ready-to-pick-up" manner, again, in a mirror configuration of the Milkrun carts (consequently, in the delivery order).

"Kanban Supermarket" is the name of the tool used to achieve this design (based on the PFEP from layer 2).

3.7. Layer 6. Inbound supply chain design.

Inbound Supply Chain connects the factory with external suppliers. Its design must be oriented toward optimizing the supermarket warehouse with frequent deliveries, thus reducing the quantities and packaging for direct delivery to the supermarket shelves.

Kanban, external Milkrun and Vendor Integration are the tools for this layer.

4. Real case of Person-Based Design implementation.

In this real case study, *Person-Based Design* was used to re-design a production area (fig. 2a) that supplied five different subassemblies to a production line with a nominal cycle time of 30 s/ut.

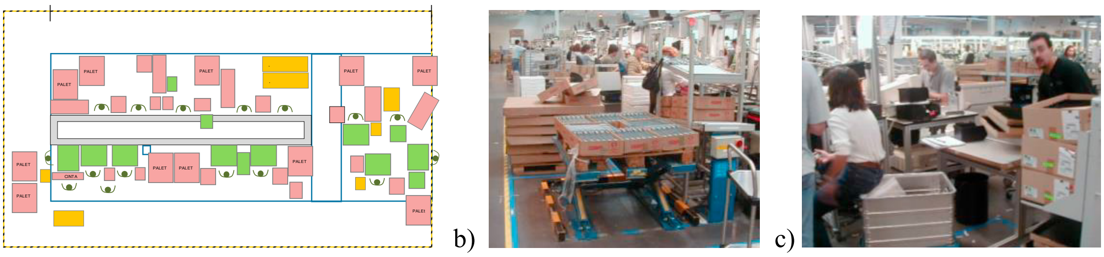
a)  b) c)

Fig. 2. Initial state: a) Layout; b) Materials around workplaces; c) Isolated workstation with high motion.

The initial production area was designed with a traditional mindset. Labor productivity was achieved through automation and work-in-process to compensate for variability among workstations. Materials were placed around workplaces to allow self-supplying if necessary (Fig. 2b). People were isolated in workstations, surrounded by big containers with high levels of motion waste (Fig. 2c).

Person-Based Design. Layer 1. The respect-for-people principle.

The redesign was performed by a cross-functional team: operators, line supervisors and process engineers. A kaizen area was set up to collect ideas for improvement and to promote continuous improvement.

Layers 2 and 3. Packaging design and the design of tools and machines.

Packaging and workstations (Fig. 3) were redesigned at the same time to achieve two main objectives:

- Improve ergonomics and reduce motion waste in order to increase labor productivity.
- Minimize the required surface in order to increase surface productivity.

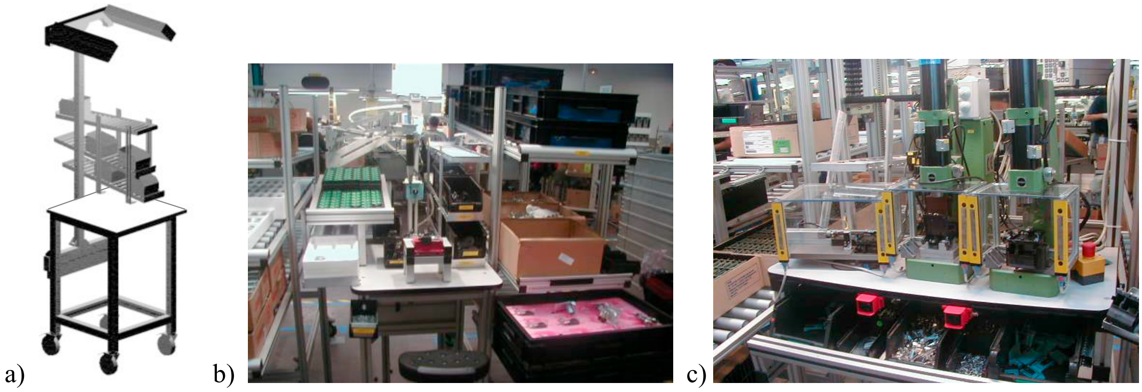


Fig. 3. a) Standard workstation design. b,c) Examples of real workplaces.

Layer 4. Production line design.

The production process was redesigned to produce one-piece-flow for every subassembly within the Takt Time of the customer line. This means that every 30 seconds the production cell produced the 5 different subassemblies within the established time.

Based on a “U-shaped” configuration, workstations were balanced to 25 seconds and the tasks from different subassemblies were combined. The work area (Fig. 4a) and supply area (Fig. 4b) were clearly independent of each other.

Layer 5. In-plant supply design.

The in-plant Milkrun route was designed to supply the line every 45 minutes from a Kanban Supermarket system set up close to the assembly area. Due to the small size of all components, only one cart was needed (Fig. 5b)

Layer 6. Warehouse design.

The warehouse was redesigned as a Kanban Supermarket (Fig. 5c). All parts were ready to pick up by the Milkrun operator. Some parts required re-packaging, which was done during the Milkrun loop using a double bin kanban system.

Layer 7. Inbound supply chain design.

The inbound supply chain was designed to fulfill the Kanban Supermarket system every 4 hours, with external Milkrun trucks following a predefined loop through different suppliers and external warehouses.

Fig. 4. a) Value-added area. b) Supply area with Milkrun. c) Kanban Supermarket

Table 1 shows the significant improvements achieved using Person-Based Design:

Table 1. Summary of achieved results

KPI	Before	After	% improvement
Work in Process (h)	13	2	550%
Surface (m^2)	102.6	57	70%
Labor Productivity (u/h/p) (including Material Handlers)	6.7	7.9	18%

Fig. 6 shows the evolution of the production area. Attention must be paid to the fact that productivity increased with one less person in the workplace. This person was re-trained to work as a Milkrun driver.

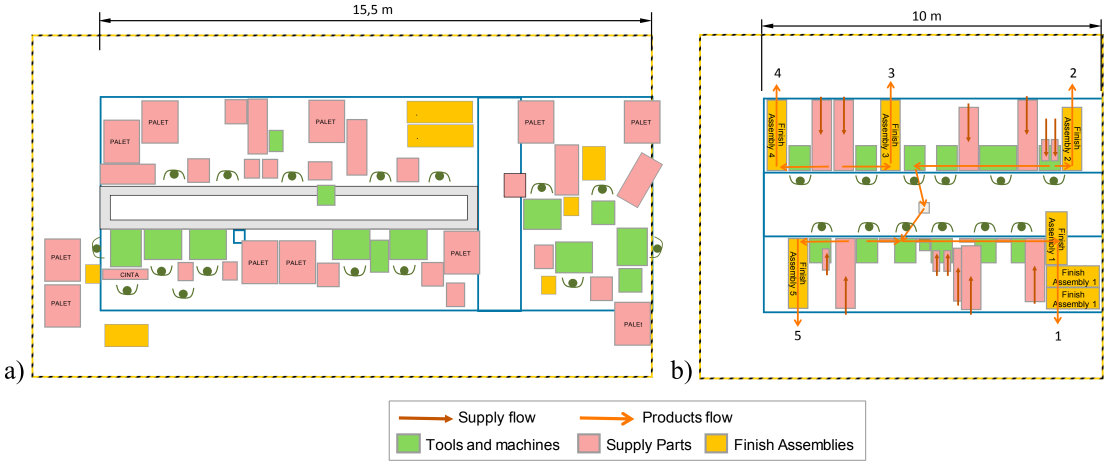


Fig. 5. Layout. a) Initial state before Person-Based Design b) U-shaped configuration showing five different product flows.

5. Case discussion.

The initial design (Fig. 5a) was based, not in “reducing waste” Principle, but in automating transportation waste with a conveyor, laying out workstations around it. Workers self-supplied their workstations and material surrounded them creating isolated work areas. Stock and transportation required more surface than value added activities despite a full-time material handler was hired to move materials and set in order the working area.

When *People Based-Design* was applied, the conveyor was eliminated, workstations were redesigned and laid out as a U-Shape Assembly line (fig. 5b), tasks were rebalanced to customer Takt Time and material handler tasks were redesigned in a Milkrun circuit. Labor and surface productivity improved as shown in Table 1.

6. Conclusions and areas for further research.

This paper introduces *Person-Based Design* as an efficient sequential method to design a Lean Factory when labor and surface productivity are key for competitiveness, thus ensuring *Respect for People*.

The *Person-Based Design* method first takes a systems perspective to integrate Lean Production principles, tools and methods. Later, the method is applied to a real case in a production area, showing significant improvement in surface reduction, WIP reduction and an increase in labor productivity (Table 1).

This research has some limitations; the most important one is lack of generalizability of case study results. Although the *Person-Based Design* method has been conceptualized as a general method, its implementation to a particular case cannot be directly generalized in other industrial settings. This pragmatic development has been performed for internal validity purposes. Future research would benefit from multiple case analyses of Person-Based Design implementation and comparison in other industrial contexts. Other open avenues for future research may include; developing the tools required at every layer of design in more detail, understanding the interactions among layers, extending research on people's perceptions and assessments in order to confirm that the *respect-for-people principle* is achieved and investigating how Person-Based Design contributes to firm competitiveness.

References

[1] J.P. Womack, D.T. Jones. D. Roos, The Machine That Changed the World. Rawson Associates, New York, 1990.
[2] T. Ohno, The Toyota Production System: Beyond Large-Scale Production, Productivity Press, 1988.
[3] M. Holweg, The genealogy of lean production, Journal of Operations Management; (2006) 420–437.
[4] Y. Sugimori, K. Kusunoki, F.Cho, S. Uchikawa, Toyota production system and Kanban system. Materialization of just-in-time and respect-for-human system. The International Journal of Production Research; 15:6, (1977) 553-564.
[5] J.H. Allen, Making lean manufacturing work for you, Journal of Manufacturing Engineering, (2000:June), 1-6.
[6] J.K. Liker, The Toyota Way, 14 Management Principles from the World's Greatest Manufacturer, McGraw-Hill, New York (2004).
[7] M.L. Emiliani, Origins of lean management in America: The role of Connecticut businesses. Journal of Management History, 12:2, (2006) 167-184.
[8] Y. Monden, Toyota Production Systems. Industrial Engineering and Management Press, Norcross, (1983) GA p:100
[9] I. Carsten, Z. Thimo, Transformation-Waves – A Brick for a Powerful and Holistic Continuous Improvement Process of a Lean Production System. Procedia CIRP 17, (2014) 582–587.
[10] W. de Kogel, J.M. Jauergui Becker, Development of Design Support Tool for New Lean Production Systems, Procedia CIRP 41 (2016) 596 – 601.
[11] P. Senge, C. Roberts, R. Ross, B. Smith, A. Kleiner, The Fifth Discipline Fieldbook: Strategies and Tools for Building a Learning Organization. Double day (1994) 93-95.
[12] B. Bidanda, P. Ariyawongrat, K. LaScola Needy, B.A. Norman, W. Tharmmaphornphilas, Human related issues in manufacturing cell design, implementation, and operation: a review and survey. Computers & industrial Engineering, 48, (2005) 507-523.
[13] J.P. Womak, D.T. Jones, Lean Thinking: banish waste and create wealth in your corporation. Simon and Schuster (2010).
[14] J. Bicheno, M. Holweg, The Lean Toolbox: a handbook for Lean transformation. Fifh edition. PICSIE books. (2016).
[15] J. Bicheno. The Lean Toolbox: A Quick and Dirty Guide for Cost, Quality, Delivery, Design and Management. PICSIE Books (1998).
[16] M. Rother, J. Shook, J. Womack, D. Jones, Learning to see. Value-stream mapping to create value and elliminate muda. The Lean Enterprise Institute, Inc. (1996).
[17] F. Gil-Vilda, A. Suñe. 5S, Manual Practico. Leanbox S.L (2011).
[18] K. Sekine, One-Piece Flow: Cell Design for Transforming the Production Process. Productivity Press (1992).
[19] R. Harris, C. Harris, E. Wilson, Making Materials Flow. Lean Enterprise Institute, Inc. (2003).
[20] F. Gil-Vilda, Milkrun, Manual Practico. Leanbox S.L (2017)
[21] F. Gil-Vilda, A. Sune, J.A. Yagüe-Fabra, C. Crespo, Serrano, Integration of a collaborative robot in a U-shaped production line: a real case study. Procedia Manufacturing 13, (2017) 109-115.
[22] F. Gil-Vilda, J.A. Yagüe, A. Suñé, J.M. Jauregui-Becker, W. Wits. A geometrical model for managing surface productivity of U-shaped assembly lines. CIRP Annals - Manufacturing Technology 67, (2018). 479–482
[23] G.R. Aase, J.R. Olson, M.J. Schniederjans, U-shaped assembly line layouts and their impact on labor productivity: An experimental study. European Journal of Operational Research 156(3) (2004):698-711.

2.3. A geometrical model for managing surface productivity of U-shaped assembly lines.

Introducido el método Diseño desde la Persona, este trabajo se centra en desarrollar las primeras capas con el enfoque de optimizar el uso de la superficie en lugar del enfoque más común que es optimizar el uso de la mano de obra.

La hipótesis de partida es la existencia de una topología que minimice el uso de la superficie en función de una serie de parámetros productivos.

Se desarrolla un modelo geométrico de Célula en U a partir del estudio empírico de varias topologías, buscando el uso óptimo del espacio. Después se identifican los diferentes parámetros productivos con influencia en el uso de superficie y se desarrolla un modelo matemático para calcular la productividad de la superficie en función de esos parámetros.

Como conclusión, la función definida no tiene un mínimo absoluto. Sin embargo, se descubre una metodología clara para poder gestionar la superficie utilizada por una célula en U y los mecanismos para poder reducirla.

Uno de los factores para regular el uso de la superficie es la frecuencia de suministro de la célula. Este hecho es el que condujo de forma lógica al siguiente artículo (desarrollado en el apartado 2.4), centrado en el diseño óptimo de circuitos de aprovisionamiento internos.

CIRP Annals - Manufacturing Technology 67 (2018) 479–482

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A geometrical model for managing surface productivity of U-shaped assembly lines

Francisco Gil Vilda [a], José A. Yagüe-Fabra (2) [b,*], Albert Sune Torrents [c], Juan M. Jauregui-Becker [d], Wessel W. Wits (2) [d,e]

[a] LEANBOX SL, Distrito 22@. C/Juan de Austria 126, Barcelona 08018, Spain
[b] I3A-Universidad de Zaragoza, C/María de Luna, 3, Zaragoza 50018, Spain
[c] Universitat Politècnica de Catalunya, C/Colom, 11, Terrassa, Barcelona 08222, Spain
[d] Department of Design, Production and Management, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands
[e] THALES Nederland B.V., P.O. Box 42, 7550 GD Hengelo, The Netherlands

ARTICLE INFO

Article history:
Available online 22 April 2018

Keywords:
Assembly
Productivity
U-shaped line

ABSTRACT

U-shaped assembly lines (U-SALs) are cellular manufacturing systems that, among other things, provide a remarkable feature for industrial cost efficiency: their effectiveness in space utilization. While the challenge of machine placement for labour productivity optimization is widely studied in the literature, surface productivity optimization has been scarcely explored. This paper proposes an industry-validated geometrical model for optimizing U-SAL surface productivity. The model links the drivers for market, product and process with the geometrical design. Managers and lean practitioners can use this approach to make decisions for layout design. The model is particularly useful in cases where the cost of floor space is substantially high.

1. Introduction

In the last ten to fifteen years, as markets are becoming more competitive and the production paradigm has shifted from mass production to mass customization, manufacturers are increasingly accommodating mixed-model assembly lines [1,2] with a particular focus on U-shaped assembly lines (U-SALs). Space optimization is becoming more and more important in this context, especially for companies that are either located in places where the cost of floor space is substantially high or that are willing to expand or update their manufacturing activity with new products that require new production capabilities and floor space. Thus, there exists a growing body of academic research exploring various facets of U-SAL design. Most of this research is focused on labour productivity. Although it is a key topic, increasing efforts towards European reindustrialization need new perspectives on productivity from a systemic point of view, in particular: surface productivity. This research induces a model to optimize U-SAL surface productivity from a multiple-case-study analysis of industrial firms.

2. U-Shaped assembly lines in literature

The Toyota Production System (TPS) was developed in Japan after 1945 as an alternative to Mass Production Systems. Taiichi Ohno (recognized as the founder of TPS) stated in an early English translation from 1978 [3]: '*In 1947, machines were arranged in the shape of the character '=''' [. . .] one operator using three machines*'. This is the first mention of the so-called 'U-Shaped Lines', a manufacturing solution for lead time reduction and cost optimization when labour costs are higher than machine amortization.

According to Miltenburg [4], the term 'U-shaped' was used for the first time in 1982 by Schonberger [5] to refer to this particular topography. He remarked the benefits in both flexibility and labour productivity. In 1983, Hall [6] mentioned 'U-shaped layout' and 'U-lines' again. Also, in 1983 Monden [7] dedicated a chapter to describing U-shaped lines as a key factor of the TPS. Monden [7] highlights *Shojinka*, meaning a flexible manpower line whose 'most remarkable advantage' is its ability to be adjusted to meet production requirements with any number of workers and changes in demand. In 1990, 'Lean Production' was introduced by Womack et al. [8] as a generic denomination for TPS. They mentioned, for the first time, the idea of surface utilization along with some other basic metrics to analyse assembly lines.

Hereafter, the analysis of surface utilization was however set aside in the research literature and the main focus turned towards increasing productivity: in 1992, Sekine [9] used the term 'U-shaped cells' and he detailed how to design them with the objective of shortening lead time and improving productivity; in 1994, Miltenburg and Wijngaard [10] introduced the U-Line Balancing (ULB) problem and showed how a U-line has much more balancing possibilities than I-lines; in 2004, Aase et al. [11] established some factors that make U-SALs more productive than their equivalent I-SALs, those factors being: higher network density, a lower number of assembly tasks and a shorter cycle time. In 2006, Kumar and Matho [12] provided an extensive

* Corresponding author.
E-mail address: jyague@unizar.es (A. Yagüe-Fabra).

https://doi.org/10.1016/j.cirp.2018.04.047
0007-8506/

literature analysis on assembly line balancing problems and formulations. In relation to ULB, they found that minimizing the number of workstations and maximizing the production rate were the commonly used objectives of the methods reviewed, with no mention being made of surface productivity as a relevant parameter.

More recent literature adds other objectives to the traditional workstation minimization problem, such as studies on the optimal operations of robots in workstations [13] and how to enable the collaboration of humans and robots on assembly lines [14,15], and the design of cells that can be optimally reconfigured [16,17]. More recent work addresses the ULB problem again but from other perspectives; e.g., Oksuz et al. [18] solved the ULB problem by also considering the worker performance. Optimization methods such as genetic algorithms have also been applied in recent years for either U-SAL balancing [19] or for optimizing the design of material handling systems of lean automation lines [20].

In summary, U-SALs have been part of the TPS since its foundation, and they are the ideal layout for 'one-piece-flow' to minimize waste in assembly processes. Their relevant advantages are:

- Lead time reduction.
- High levels of labour productivity due to:
  - Avoiding operator wait time for machines.
  - Multiplying balancing possibilities.
- Adaptability (*Shojinka*): throughput variation by adding or removing operators inside the U space.
- Very efficient surface utilization due to:
  - Work in process elimination.
  - Workstations and machines placed close together.

As can be seen from the presented literature review, the U-SAL optimization problem has once again become a relevant research topic. However, most scientific studies, even those published after 2016 [21,22], focus mainly on workstation minimization, on lead time reduction and on labour productivity optimization, as Miltenburg and Wijngaard [10] stated in their ULB problem. Although labour productivity is a relevant topic, the increasing implementation of U-SALs in manufacturing facilities requires new perspectives of productivity from a systemic point of view.

In this context, this paper presents a U-SAL surface productivity management and optimization method, which is particularly relevant nowadays for many industries located where the cost of floor space is substantially high or where surface constraints limit the possibilities of spatial growth for factories that seek to expand their manufacturing capabilities.

This study is based on an inductive approach. The determination of the analytic model is based on the modelling approached designed in Ref. [23]. To this end, a multiple case study analysis has been carried out with industry-validated solutions, which have been selected as successful cases in their respective factories due to their optimal use of space in obtaining high productivity.

3. Field study

To conduct a systematic observation, the following parameters have been measured and calculated for each case study:

- Q = Maximum throughput (units per hour: u/h)
- N = Number of workstations (–)
- S = Total surface without aisles (m^2)
- S_u = Surface of the product (m^2)

From these parameters different ratios have been calculated in order to characterise each U-SAL in terms of surface usage. These ratios are defined in Table 1. Tables 2–6 show the values for both the parameters and the ratios of five different U-SALs used to assemble five different products of relatively small sizes and short single assembly tasks.

Table?1
Ratio definitions for cross-case analysis of surface use.

Ratio	Meaning
$SP = Q/S$ [8]	Efficiency in the use of the surface (surface productivity) in units/hour/m^2 (u/h/m^2).
$WS = S/N$	Compaction of workstations (m^2).
$WS_u = S/S_u$	Number of products that can be placed on the U-SAL surface (–).

Table 2
Case 1: characterisation of printer carriage U-SAL.

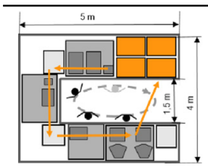
Topography	Data	Value	Comments
	Q	60 u/h	Manual assembly
	S	20.0 m^2	
	N	3	
	S_u	0.03 m^2	
	SP	3.0 u/h/m^2	
	WS	6.7 m^2	
	WS_u	667	

Table 3
Case 2: characterisation of car light U-SAL.

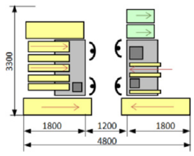
Topography	Data	Value	Comments
	Q	120 u/h	Manual assembly with soft automation
	S	15.8 m^2	
	N	4	
	S_u	0.09 m^2	
	SP	7.5 u/h/m^2	
	WS	3.9 m^2	
	WS_u	176	

Table 4
Case 3: characterisation of engine filter U-SAL.

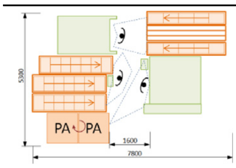
Topography	Data	Value	Comments
	Q	110 u/h	Semi-automated assembly with large welding machine
	S	41.4 m^2	
	N	3	
	S_u	0.12 m^2	
	SP	2.7 u/h/m^2	
	WS	13.8 m^2	
	WS_u	335	

Table 5
Case 4: characterisation of car exhaust pipe U-SAL.

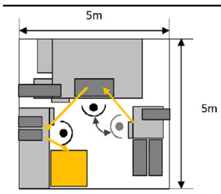
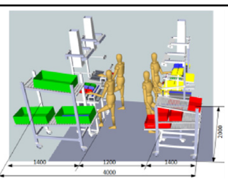
Topography	Data	Value	Comments
	Q	25 u/h	Manual assembly plus automatic welding
	S	25.0 m^2	
	N	2	
	S_u	0.12 m^2	
	SP	1.0 u/h/m^2	
	WS	12.5 m^2	
	WS_u	208	

Table 6
Case 5: characterisation of light sabre toy U-SAL.

Topography	Data	Value	Comments
	Q	15 u/h	Manual assembly
	S	8.0 m^2	
	N	4	
	S_u	0.10 m^2	
	SP	1.9 u/h/m^2	
	WS	2.0 m^2	
	WS_u	80	

By comparing the ratios (Table 7), the best solutions have been identified and analysed in order to find the key factors for their high performance. The best values are in bold in Table 7.

Table 7
Ratio results for the industry study cases.

Case	*SP*	*WS*	WS_u
1?— Printer carriage	3.0	6.7	667
2?— Car light	**7.5**	**3.9**	**176**
3?— Engine filter	2.7	13.8	335
4?— Car exhaustion pipe	1.0	12.5	208
5?— Light sabre	1.9	**2.0**	**80**

In terms of compaction of the space (*WS*), the best ratios are obtained in cases 2 and 5, where the smallest values are found. Therefore, the U-SALs of cases 2 and 5 demonstrate good topography in the sense of not being a ‘U’, but an ‘=’; i.e., two parallel lines without a third side closing the ‘U’.

In terms of the efficiency of surface usage or surface productivity, high values of *SP* are expected as well. In case 2, the highest value of *SP* can be found. This means that less time to assemble one unit is required. From this correlation, it can be inferred that product assembly time is one of the factors that determines surface requirements, as it influences the number of workstations.

Product size is another factor that could influence surface. WS_u measures how compact the solution is in relation to product surface. Therefore, low values for this ratio are sought. Again, cases 2 and 5 show better results due to their ‘=’ topographies.

Case 3 also has an ‘=’ topography similar to those of cases 2 and 5, but its *WS* and WS_u ratios are worse. The reason for this is the large size of the machinery needed in case 3, as well as the large amount and size of materials stored in the cell. From these observations, it can be inferred that the supply process also influences the required space, as the supply process determines the amount of stored materials in the U-SAL.

4. General model definition

Three main elements influence the surface needed in a U-SAL: people (ergonomic space), workstations (machinery) and materials. These elements are determined by market, product and process requirements (see Table 8).

Table 8
Factors influencing surface needs.

	Factor	Connection and notation
Market	Customer demand	Customer demand (D) sets the takt time (TT) that influences the throughput (Q).
Product	Complexity	Defines the manual assembly time (T_{ma}). Defines the number of components to be stored in the workstation.
	Size	Defines the minimum workstation surface for handling the product.
Process	Technology	Defines the machinery size. Defines the automatic assembly time (T_{au}).
	Supply process	Defines the fulfilment cycle (C_f) and, thus, the quantity of components at the workstation.
	Production process	Defines the throughput (Q) and cycle time (T_C).

Some design factors have been simplified by choosing the best-case possibility in terms of surface reduction. This ‘as good as it gets’ (AGAIG) criterion has reduced the model’s complexity.

The U-SAL topographies can be generally characterised by the geometrical configuration shown in Fig. 1.

In addition, with the AGAIG criterion, the workstation width, h_i, cannot be less than the ergonomic space needed for a standard person, *h*. This is a realistic situation for a wide range of cases with the following characteristics:

(a) Product size does not influence h_i.
(b) Quantity and dimensions of parts do not influence h_i.
(c) Machine and tooling processes do not influence h_i.

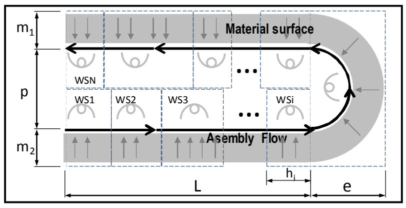


Fig. 1. General topography for a U-SAL with *N* workstations.

Thus, a more compact topography can be defined by the shape of the character ‘=’, as described by Ohno in Ref. [3] and also concluded from the cases studied in Section 3.

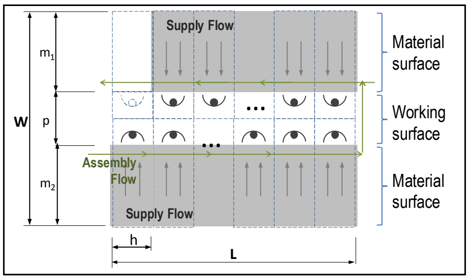


Fig. 2. AGAIG topography for a number *N* of workstations.

Surface productivity (*SP*) is defined as the ratio between throughput (*Q*) and surface (*S*) to meet this throughput.

$$SP = \frac{Q}{S} \quad \text{where} \quad Q = \frac{1}{T_C} \quad \text{and} \quad S = W \cdot L \rightarrow SP = \frac{1}{T_c \cdot W \cdot L} \tag{1}$$

If *h* is the same for all workstations, then U-SAL length (*L*) is:

$$L = \left[\frac{N}{2}\right] \cdot h \tag{2}$$

where *N* is the total number of workstations. With the AGAIG criterion, *N* is minimum if a perfect split of assembly tasks among the workstations is possible and operators never have to wait for the machine. In this situation:

$$N = \left[\frac{T_{ma}}{T_c}\right] \Rightarrow L = \left[\frac{\left[\frac{T_{ma}}{T_c}\right]}{2}\right] \cdot h \Rightarrow L = \left[\frac{T_{ma}}{2 \cdot T_c}\right].h \tag{3}$$

The U-SAL width *W* is defined as:

$$W = p + m_1 + m_2 \tag{4}$$

where m_1 and m_2 are determined by the quantity of the worst part (*WP*) in terms of surface occupation at the workstation. Considering the worst part on each side of the U-SAL, a density factor can be defined as:

$$\alpha_1 = \frac{m_1}{WP_1}; \alpha_2 = \frac{m_2}{WP_2} \tag{5}$$

The number of parts stored at the workstations must be at least enough to cover the Fulfilment Cycle (C_f); otherwise, the U-SAL stops. So, the number of each part to be stored is:

$$Parts_i = \frac{C_f}{T_c} \cdot n_i \tag{6}$$

where n_i is the number of $Part_i$ per product.

In particular, considering the worst part as described:

$$m_1 + m_2 = \alpha_1 \cdot n_1 \cdot \frac{C_f}{T_c} + \alpha_2 \cdot n_2 . \frac{C_f}{T_c} = (\alpha \cdot n_1 + \alpha_2 \cdot n_2 .) \cdot \frac{C_f}{T_c}$$
$$\Rightarrow W = p + \delta \frac{C_f}{T_c} \tag{7}$$

where $\delta = (\alpha \cdot n_1 + \alpha_2 \cdot n_2)$ is a density factor defined by the shape of the worst parts and how they can be compacted inside containers.

Therefore, the total surface can be determined as

$$S = \left(p + \delta \cdot \frac{C_f}{T_c}\right) \cdot \left[\frac{T_{ma}}{2 \cdot TC}\right] \cdot h = (p + \delta \cdot C_f \cdot Q) \cdot \left[\frac{T_{ma} \cdot Q}{2}\right] \tag{8}$$

and thus the surface productivity can be formulated as:

$$SP = \frac{1}{S \cdot T_c} = \frac{1}{\left(p + \delta\frac{C_f}{T_c}\right) \cdot \left\lceil \frac{T_{ma}}{2T_c} \right\rceil \cdot h} \quad (9)$$

By applying this mathematical model to typical values in industry, Fig. 3 shows the evolution of surface to throughput and surface productivity to cycle time in a graphical way.

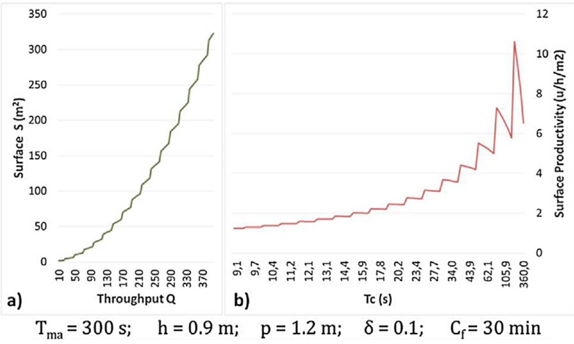


Fig. 3. For typical industrial values: (a) surface (S) vs. throughput (Q); (b) surface productivity (SP) vs. cycle time (T_c).

5. Discussion

The presented model supports the following new findings:

- Surface needs have a quadratic relationship with throughput, which can be derived from Eq. (8).
- Once the cycle time is defined, the length is set and the width is only proportional to the fulfilment cycle. By doing so, surface needs can be easily managed.
- There is no single optimum for surface productivity in relation to the cycle time, which makes cycle time an independent variable in such types of decisions.
- There are, however, some cycle times that maximize surface productivity locally (see Fig. 3b).

In a lean production system context, one of the most important principles is to 'produce accordingly to customer takt time'. This means that in an ideal situation: $T_c = TT$.

However, in a more realistic way: $T_c < TT$ or $Q > D$.

Once the takt time is set and the product and parts are well defined for complexity and size, the proposed model guides the decision-making process about surface optimization as follows:

First: As the surface has a quadratic relationship with the throughput, setting up several U-SALs is more efficient than only one. This is particularly important when the cycle time is much less than the manual assembly time (Eq. (8)). Notice that this decision has an impact on capital investment.

Second: Once a decision on the number of U-SALs is made, the cycle time can be fine-tuned in order to locally maximize the surface productivity.

Third: If there are strong surface constraints, the fulfilment cycle can be reduced, lowering m_1 and m_2, and consequently reducing the surface requirements (see Fig. 2). Notice that, with such a systemic view, this option has a direct impact on the effectiveness of the fulfilment process.

6. Conclusions and future research

This research examined surface productivity of U-SALs. Departing from five industry-validated U-SALs, the cross-case analysis showed that (1) better solutions regarding surface productivity are found when workstations are arranged in two parallel lines like an "=" without a third side closing the "U", (2) product assembly time determines the surface requirements as it influences the number of workstations, (3) the supply process also influences the required space, as the fulfilment cycle determines the number of materials stored in the U-SALs.

Considering the field study conclusions a geometrical model for managing and optimizing surface productivity in U-SALs has been defined. The proposed geometrical model integrates multiple factors, including market, product and process factors to guide the final layout design of U-SALs. Some simplifications have been introduced, which are particularly realistic for small products with short single assembly tasks. The model sets the surface requirements based on three main variables: throughput, cycle time and fulfilment cycle. In all cases, the model calculates an 'as good as it gets' surface requirement, which is very useful during layout design and optimization.

This paper also leaves some open questions that need further research:

- If the produced parts are large or numerous and the quantity of workstations are below a certain number, the workstation width (h_i) increases. This means that $h_i = f(N)$ must be considered.
- There should be further analysis of how the fulfilment cycle impacts the dimensions of aisles and, consequently, surface productivity.
- Studies could be developed on potential optimal supply cycle which might maximize logistics productivity.
- A model for a plant layout based on U-SAL and milk run circuits that optimize surface productivity could be proposed.

References

[1] Jovane F, Koren Y, Boer CR (2003) Present and Future of Flexible Automation: Towards New Paradigms. *CIRP Annals — Manufacturing Technology* 52(2):543–560.
[2] Bley H, Zenner C (2006) Variant-oriented Assembly Planning. *CIRP Annals — Manufacturing Technology* 55(1):23–28.
[3] Ohno T (1988) *Toyota Production System: Beyond Large-scale Production*, American edition. Productivity Press, Cambridge, Massachusetts.
[4] Miltenburg J (2001) U-shaped Production Lines: A Review of Theory and Practice. *International Journal of Production Economics* 70(3):201–214.
[5] Schonberger R (1982) *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*, Simon and Schuster: 139–144.
[6] Hall RW (1983) *Zero Inventories*, Irwin Professional Pub. p. 120.
[7] Monden Y (1983) *Toyota Production Systems*, Industrial Engineering and Management Press, Norcross, GA. p. 100.
[8] Womack JP, Jones DT, Roos D (1990) *Machine That Changed the World*, Simon and Schuster, New York.
[9] Sekine K (1992) *One-piece Flow: Cell Design for Transforming the Production Process*, Productivity Press, Cambridge, Massachusetts.
[10] Miltenburg GJ, Wijngaard J (1994) The U-line Line Balancing Problem. *Management Science* 40(10):1378–1388.
[11] Aase GR, Olson JR, Schniederjans MJ (2004) U-shaped Assembly Line Layouts and Their Impact on Labor Productivity: An Experimental Study. *European Journal of Operational Research* 156(3):698–711.
[12] Kumar N, Mahto D (2013) Assembly Line Balancing: A Review of Developments and Trends in Approach to Industrial Application. *Global Journal of Research in Engineering* 3(2):1–23.
[13] Mukund Nilakantan J, Ponnambalam SG (2016) Robotic U-shaped Assembly Line Balancing Using Particle Swarm Optimization. *Engineering Optimization* 48(2):231–252.
[14] Krüger J, Lien TK, Verl A (2009) Cooperation of Human and Machines in Assembly Lines. *CIRP Annals — Manufacturing Technology* 58(2):628–646.
[15] Gil-Vilda F, Sune A, Yagüe-Fabra JA, Crespo C, Serrano H (2017) Integration of a Collaborative Robot in a U-shaped Production Line: A Real Case Study. *Procedia Manufacturing* 13:109–115.
[16] Manzini M, Unglert J, Gyulai D, Colledani M, Jauregui-Becker JM, Monostori L, Urgo M (2018) An Integrated Framework for Design, Management and Operation of Reconfigurable Assembly Systems. *Omega* 78:69–84.
[17] Unglert J, Jauregui-Becker JM, Hoekstra S (2016) Computational Design Synthesis of Reconfigurable Cellular Manufacturing Systems: A Design Engineering Model. *Procedia CIRP* 57:374–379.
[18] Kursat Oksuz M, Buyukozkan K, Itir Satoglu S (2017) U-shaped Assembly Line Worker Assignment and Balancing Problem: A Mathematical Model and Two Meta-heuristics. *Computers & Industrial Engineering* 112:246–263.
[19] Alavidoost MH, Fazel Zarandi MH, Tarimoradi M, Nemati Y (2014) Modified Genetic Algorithm for Simple Straight and U-shaped Assembly Line Balancing with Fuzzy Processing Times. *Journal of Intelligent Manufacturing* 28(2):313–336.
[20] Yamazaki Y, Shigematsu K, Kato S, Kojima F, Onari H, Takata S (2017) Design Method of Material Handling Systems for Lean Automation — Integrating Equipment for Reducing Wasted Waiting Time. *CIRP Annals — Manufacturing Technology* 66(1):449–452.
[21] Alavidoost MH, Babazadeh H, Sayyari ST (2017) An Interactive Fuzzy Programming Approach for Bi-objective Straight and U-shaped Assembly Line Balancing Problem. *Applied Soft Computing* 40:221–235.
[22] Tiacci L (2017) Mixed-model U-shaped Assembly Lines: Balancing and Comparing with Straight Lines with Buffers and Parallel Workstations. *Journal of Manufacturing Systems* 45:286–305.
[23] Jauregui-Becker JM, Wits WW (2013) An Information Model for Product Development: A Case Study at PHILIPS Shavers. *Procedia CIRP* 9:97–102.

2.4. An in-plant milk-run design method for improving surface occupation and optimizing mizusumashi work time.

Continuando con el desarrollo del método Diseño desde la Persona, y una vez descrita la influencia que el ciclo de aprovisionamiento tiene en el consumo de superficie de las Células de Producción, este artículo se centra en desarrollar la capa cinco del modelo (suministro interno).

Para ello se define una metodología de diseño de un circuito milk-run interno conducido por una persona, enfocada al uso mínimo del espacio.

A partir de este método de diseño se observa que el periodo de suministro tiene dos efectos contrapuestos respecto a la carga de trabajo del conductor: a mayor periodo, menor tiempo de conducción línea-almacén, pero mayor longitud del tren y, por tanto, mayor tiempo del conductor recorriendo el tren máquina-vagones. Surge, en consecuencia, la hipótesis de que existe un ciclo óptimo que minimiza la carga de trabajo del conductor.

Introduciendo algunas simplificaciones coherentes con la praxis observada en entornos reales para este tipo de suministro, se llega a una formulación matemática discreta que, en efecto, tiene un mínimo. Una aproximación continua permite, por derivación, encontrar una ecuación para hallar ese mínimo.

Los resultados constituyen una guía de diseño muy valiosa cuando el coste de la superficie es elevado (por el valor del suelo, o por el coste de mantenimiento de la superficie como, por ejemplo, una sala blanca) y/o cuando el producto fabricado es voluminoso.

CIRP Annals - Manufacturing Technology 69 (2020) 405–408

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

An in-plant milk-run design method for improving surface occupation and optimizing *mizusumashi* work time

Francisco Gil Vilda[a], José A. Yagüe-Fabra (2)[b,*], Albert Sunyer Torrents[c]

[a] LEANBOX SL, Distrito 22@. C/ Juan de Austria 126, Barcelona 08018, Spain
[b] I3A- Universidad de Zaragoza, C/ María de Luna, 3, Zaragoza 50018, Spain
[c] Universitat Politècnica de Catalunya, C/ Colom, 11, Terrassa, Barcelona 08222, Spain

ARTICLE INFO

Article history:
Available online 16 May 2020

Keywords:
Logistics
Productivity
In-plant milk-run

ABSTRACT

Product customization is becoming a competitiveness factor in most markets. It implies manufacturing small and varied batches in mixed-product assembly lines and frequently supplying parts to production lines in small quantities with high efficiency. The in-plant milk-run is a specific tool used in this context. This paper proposes an industry-validated design method for human-driven milk-runs, based on improving surface productivity. A mathematical model is defined for relating *mizusumashi* work time to the milk-run period and finding its minimum value. This research is particularly useful in factories with high cost per m^2 supplying high-volume parts.

1. Introduction

The general trend in highly competitive markets is to increase product variety to fulfil diverse customers' needs. This is one of the reasons why manufacturers currently receive more fragmented demand. Thus, designing a flexible production system able to work efficiently with small and varied batches constitutes a key competitive factor.

Lean Production Systems are well adapted to this context. They are based on the Toyota Production System, developed as a 'multi-kind, small-quantity production system' based on 'the absolute elimination of waste' [1]. 'Transporting' and 'Motion' are two of the 7 wastes, critical to logistic optimization.

Baudin [2] introduced the concept of in-plant Lean Logistics to efficiently supply parts to mixed-product assembly lines that produce small batches. The in-plant milk run is one of the tools that serve this purpose. It consists of a transportation system that delivers materials from a storage area to several points of use (POUs) on defined routes in short and fixed periods. During this period, the material handler (*mizusumashi*) picks up containers at the storage areas; follows a predetermined standard route using multi-coach trains; delivers them to various POUs; and on the return trip bring empty containers back to the source [3]. The milk run has been reported to be suitable for handling materials in repetitive pull-flow production for high product mix [4,5].

2. Literature review

Toyota reported that *mizusumashi* was first introduced in 1955 and evolved in 1977 to a multi-stop delivery system [6]. In 1982, Schonberger [7] used for the first time the term "water beetle" (English translation for *mizusumashi*) referring to the in-bound logistics of making numerous trips to move parts in very small quantities. Recent papers apply the term *mizusumashi* to the handler who operates the milk run: A handler who supplies only the necessary items in the necessary quantities at the necessary time [8]. This paper uses the term *mizusumashi* for the handler tasks, and milk run for the in-plant transportation system.

Nomura and Takakuwa [9] developed a mathematical milk-run model for determining the minimal number of containers necessary for supplying parts to assembly lines considering work time and inventory levels. Further mathematical models can be found to address the problem of how to allocate containers to tours [10], to design and manage the milk-run and inventory levels driven by *kanban* systems [11], to schedule and load tugger trains [12] and to examine *mizusumashi's* utilization and impact on the manufacturing system [13].

A review and categorization of in-plant milk runs reported that material handling occupies 55% of a factory's surface [14]. Recent research on milk-run design, such as the Vehicle Routing Problem (VRP), has focused mainly on minimizing the total distance travelled or minimizing the number of vehicles applied [15,16] but less attention has been paid to milk-run design for surface reduction and handling productivity [17].

This study is based on mathematical modelling and actual practice for milk-run design, focusing on surface and labour productivity, which is supplemental to VRP perspective. It proposes an in-plant milk-run design method for reducing surface requirements as a main goal and, under these boundary conditions, minimizing *mizusumashi* work time.

3. In-plant milk-run design method for surface reduction

This analysis uses the following terminology: an in-plant milk run takes place during working time S and delivers n different parts

* Corresponding author.
E-mail address: jyague@unizar.es (J.A. Yagüe-Fabra).

https://doi.org/10.1016/j.cirp.2020.03.012

Table 1
Notation and empirical values collected in a case study.

	Description	Notation	Case study values
Milk-run loop	Supply time (working time)	S	480 min (1 shift)
	Frequency (loops per S)	F	–
	Milk-run period (S/F)	P	–
	Transportation time for one loop	T_t	4 min
	Number of points of use (POU)	m	12 POUs
	Parts to supply	n	$2{\cdot}m$
	Number of coaches	N	–
POU	POU consumption cycle time	C_t	40 s
Coach	Coach length	L_v	120 cm
	Coach width	W_v	60 cm
	Coach height	H_v	100 cm
	Coach walking length= $L_v + W_v/2$	L	150 cm
Container	Container length	L_c	60 cm
	Container width	W_c	40 cm
	Container height	H_c	25 cm
	Units per container	u	8 parts
Motion	Time to manipulate one container	T_h	2 s
	Time to walk a step by *mizusumashi*	T_w	0.8 s/m
	Walking distance per loop	D	–
Ratios	Container volume	$L_c \cdot W_c \cdot H_c$	0.06 m^3
	Coach Volume	$L_v \cdot W_v \cdot H_v$	0.72 m^3
	Number of containers per coach	M	12
	$\alpha = n/(M \cdot u)$	α	0.21

within a replenishment period P to m POUs that consume the parts at a C_t cycle time (notation in Table 1).

3.1. Surface reduction factors

Surface plant consumption due to internal logistics processes are related, at least, with two main factors:

1. Aisles surface to ensure space is enough for material transportation and ergonomic handling (Fig. 1.)
2. Surface used by full and empty containers laid at the POUs.

Milk-run design method influences both factors as follows:

1. Aisles surface occupied is defined by aisle length and width. Minimum width requirements are set by the coach width plus the minimum distance to ensure a safe handling from the coach to the POU (Fig. 1a).
2. Surface occupied by containers is proportional to the number of containers required by the POU for a non-stop production. According to [9], the number of containers (N_c) at a POU that are replenished every P time by a *mizusumashi* can be calculated by Eq. (1):

$$Nc = \frac{P + LT}{C_t \cdot u} \tag{1}$$

Where LT is the time since the *mizusumashi* sees the container needs to the moment he comes back and supplies the POU; u is the number of parts per container and C_t is the consumption cycle time at the POU.

There are two ways to reduce N_c and, therefore, the surface needed at the POU:

- Make $LT \rightarrow 0$. The maximum number of containers consumed by a POU during P is $\frac{P}{C_t \cdot u}$. If coach preloads this number of containers, supplies can be delivered immediately, and LT becomes negligible. This approach is coined 'preloading method'.

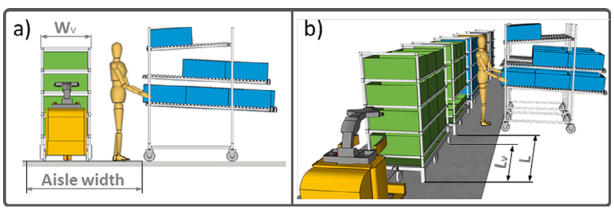


Fig. 1. *Mizusumashi* supplying a POU. a) Front view; b) 3D view.

- Reduce P as much as possible. This is particularly relevant because, accordingly to [17], production cells surface has a quadratic relationship with P. Nevertheless, P reduction has some limits: the shorter the P, the more trips from storage to POUs are needed, so more driving time is added to *mizusumashi* workload.

Therefore, three rules can be issued for a design method oriented towards reducing surface occupation:

1. Minimizing coach width (W_v) to minimize aisle surfaces.
2. Using the 'preloading method' to minimize *mizusumashi's* lead time and the number of containers at POUs (Eq. (1)).
3. Shortening the replenishment period (P) to reduce the production line surface due to containers at its POUs [17].

The next step in this study is to model the *mizusumashi*'s work time in order to calculate P for a minimum work time, always within the boundary conditions established by the three mentioned rules.

3.2. Milk-run period (P) for minimum mizusumashi work time

Even though a short P is preferred for minimizing the production line surface, P has a direct impact on the *mizusumashi*'s workload (WL) during the supply time (S), which is calculated as the work time in Eq. (2):

$$WL = driving\ time + handling\ time + walking\ time$$
$$= WL_d + WL_h + WL_w \tag{2}$$

Eq. (2) components are studied below aiming to minimize the work time function. The notation used is shown in Table 1:

Driving time (WL_d) during the supply time (S) is calculated by Eq. (3):

$$WL_d = number\ of\ loops \cdot T_t = \frac{S}{P} \cdot T_t = F \cdot T_t = f\left(\frac{1}{P}\right) \tag{3}$$

Therefore, driving time can be expressed as a reverse function of the milk-run period (P).

Handling time (WL_h) for loading and unloading containers during the supply time (S) is calculated by Eq. (4):

$$WL_h = \sum_{i=1}^{n} \left(4 \cdot \frac{S}{C_{ti} u_i} \cdot T_{hi}\right) \tag{4}$$

Where i is the type of part to be supplied and u_i is the number of units of part i inside its container.

Note that every container is handled 4 times: 2 times (full, empty) at POU and 2 times (empty, full) at the storage area.

Thus, once the workstation cycle time (Ct_i) is defined for each part and the container geometry is defined, handling time during S time becomes a constant that remains independent of the milk-run period (P).

Walking time (WL_w) up and down the train during the supply time (S) is proportional (Fig. 2) to the number of coaches (N). Using the 'preloading method', defined in Section 3.1, N can be calculated solving the Bin Packing Problem (BPP) [18,19] or by Eq. (5) if standard containers fit perfectly in the coach.

$$N = \frac{Volume\ of\ preloaded\ containers}{Volume\ of\ the\ standard\ coach}$$
$$= \frac{\sum_{i=1}^{n} \left[(L_{ci} \cdot W_{ci} \cdot H_{ci}) \cdot \frac{P}{C_{ti} \cdot u_i}\right]}{L_v \cdot W_v \cdot H_v} \tag{5}$$

Thus, walking time is proportional to the milk-run period (P) and, therefore, a function of it.

In conclusion, the total *mizusumashi* work time (WL) during the supply time (S) defined in Eq. (2) can be simplified and expressed in terms of the milk-run period (P), as in Eq. (6):

$$WL(P) = f_1\left(\frac{1}{P}\right) + Constant + f_2(P) \tag{6}$$

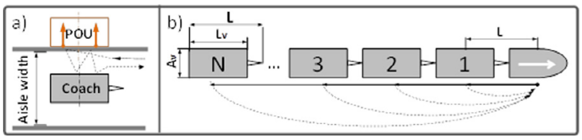


Fig. 2. a) Dimensions of the milk-run coach and POU; b) *Mizusumashi* walking schema up and down the train in every loop.

Once having established a mathematical relationship between WL and P, a question arises: Is there an optimum milk-run period (P) that minimizes WL? To answer this question, the model must include walking time (WL_w), which is the third term in Eq. (6), and therefore walking distance.

3.3. Modelling the stopping strategy and walking time

This key point has been developed based on directly observing industrial milk-run systems in different plants and interviewing experienced *mizusumashis*. As a result, the following restrictions have been introduced:

- The coach should stop in front of the POU in order to optimize handling motion. POUs width should be as close as possible to coach length (Fig. 1b, 2a).
- From an ergonomic point of view, the *mizusumashi* should walk the minimum distance while carrying full containers. Thus, he should go to the head of the train and move it forward to place every coach in front of its POU.

Under these conditions, the *mizusumashi* walks as shown in Fig. 2b, twice every loop (once in the production area to supply the POUs, and another time while in the storage area to load the train). Therefore, this walking distance per loop (D) can be expressed as in Eq. (7). Bear in mind that D is an arithmetic progression.

$$D = 2\cdot(2L + 4L + 6L + \cdots + 2\mathrm{NL}) = 4\cdot L\sum_{i=1}^{N} i \; = 4\cdot L\cdot N\cdot\frac{1+N}{2} \qquad (7)$$

Notice that this approach is valid if every coach loads parts for a single POU, which is realistic when $N \geq m$. This is also the case when supplying large parts (focus of this research).

In such a situation, walking time (WL_w) during the supply time (S) can be formulated as in Eq. (8).

$$WL_w = \frac{S}{P}\cdot D\cdot T_w = 2\cdot\frac{S}{P}\cdot L\cdot N\cdot(N+1)\cdot T_w \qquad (8)$$

If $N<m$, every coach must stop at several POUs, and the *mizusumashi* must walk the distance D several times. m/N could be considered a correction factor in this case.

3.4. Final formulation for mizusumashi work time (WL)

In summary, *mizusumashi* work time (WL) can be expressed, according to Eq. (2) and Eq. (6), as the sum of: the driving time (WL_d), which is expressed in Eq. (3); the handling time (WL_h), shown in Eq. (4); and the walking time (WL_w) that is indicated in Eq. (8). The final expression is shown in Eq. (9):

$$WL = \frac{S}{P}T_t + \sum_{i=1}^{n}\left(4\cdot\frac{S}{C_{ti}}\cdot\frac{1}{u_i}\cdot T_{hi}\right) + 2\cdot\frac{S}{P}\cdot L\cdot T_w\cdot N\cdot(N+1) \qquad (9)$$

where N is calculated according to Eq. (5). As mentioned above, this is valid when supplying large parts.

4. Discussion

As shown in Eq. (9), the *mizusumashi's* workload (WL) is a discrete function because both, the number of containers and the number of coaches, are natural numbers. Therefore, its minimum cannot be calculated by derivation, but it can be obtained by graphical analysis. This is done in Section 4.2.

However, expressing WL as a continuous function could help us to understand the relationships between the different variables, especially between P and WL. An approach to that is described in Section 4.1.

4.1. WL continuous function approach

In order to simplify the formulation for the abovementioned continuous function, some adjustments are made: First, we consider standard containers with the same dimensions and the same parts inside; second, the workstation cycle time (C_t) will be the same at every POU.

With these assumptions, we can simplify Eq. (5), which calculates the number of coaches (N). This is shown in Eq. (10):

$$N = \frac{\sum_{i=1}^{n}\left[(L_{ci}\cdot A_{ci}\cdot H_{ci})\cdot\frac{P}{C_{ti}\cdot u_i}\right]}{L_v\cdot A_v\cdot H_v} = \frac{n\cdot P\cdot(L_{ci}\cdot A_{ci}\cdot H_{ci})}{L_v\cdot A_v\cdot H_v\cdot T_c\cdot u} = \frac{n\cdot P}{M\cdot C_t\cdot u} = \alpha\cdot\frac{P}{C_t} \qquad (10)$$

where M is the number of containers per coach and the ratio $\alpha = n/(M\cdot u)$, n is the number of parts to supply, and u is the number of parts per container.

With N calculated as in Eq. (10), the walking time (WL_w) could be calculated by Eq. (8). The total *mizusumashi* work time (WL) defined by Eq. (9) can be expressed as in Eq. (11).

$$WL(P) = \frac{S}{P}\cdot T_t + Constant + 2\cdot\frac{S}{P}\cdot L\cdot\alpha\cdot\frac{P}{C_{tc}}\cdot\left(\alpha\cdot\frac{P}{C_t}+1\right)\cdot T_w \qquad (11)$$

This expression allows minimizing the *mizusumashi* work time during the milk-run period (P), doing so by derivation, i.e., making $dWL/dP=0$, as shown in Eq. (12).

$$\frac{dWL}{dP} = -\frac{S}{P^2}\cdot T_t + \frac{2\cdot S\cdot L\cdot\alpha^2\cdot T_w}{C_t^2} = 0 \qquad (12)$$

By clearing P from Eq. (12), Eq. (13) is obtained. This can then be used to calculate the optimum milk-run period (P) for a minimum *mizusumashi* work time under the assumptions mentioned at the beginning of this subsection.

$$P = \frac{C_t\cdot M\cdot u}{n}\sqrt{\frac{T_t}{2\cdot L\cdot T_w}} \qquad (13)$$

4.2. Graphical analysis for calculating optimum P

As mentioned above, WL is a discrete function and therefore we can use graphical analysis to obtain general results without applying simplifications.

A case analysis has been developed based in a real process from a production plant located in Zaragoza (Spain). The studied product is a car component built by 4 large plastic parts, moulded and later assembled in U-Shaped cells in the same plant. An internal milk-run transfers these parts from the moulding supermarket (Fig. 3a) to cells' POUs (Fig. 3b). Two parts are supplied to each POU ($n = 2\,m$). Empirical values collected from the company are shown in Table 1.

The main goal of this analysis is to obtain the optimal milk-run period (P) that minimizes the *mizusumashi*'s total work time (WL). To that end, Eqs. (3), (4) and (8) are applied for calculating the three components of WL (WL_d, WL_h and WL_w, respectively) (see Fig. 4), and Eq. (9) is then used to calculate total WL. In Fig. 5, WL is calculated for different numbers of POUs (m) in order to study their relationships.

When $N<m$, the correction factor defined in Section 3.3 is applied to Eq. (9) in order to obtain more realistic results.

Fig. 3. a) Supermarket; b) Typical POU; c) Milk-run facing a POU.

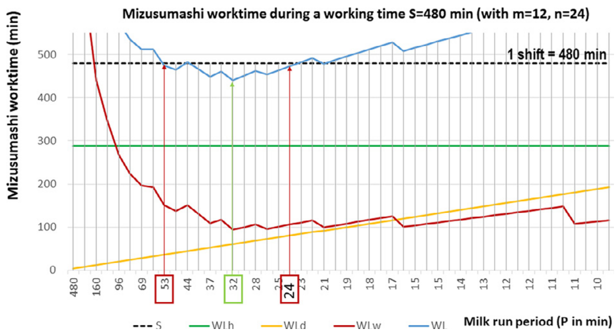


Fig. 4. Graphical analysis of the real case with large parts: work time is a function of the milk-run period (P) for a work time S of 480 min (1 shift), with 12 POUs and 24 delivery parts.

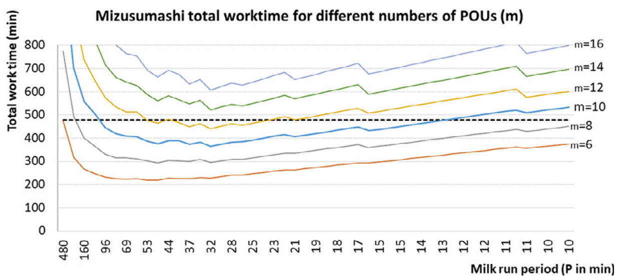


Fig. 5. Work time versus number of POUs m, with $n = 2 \cdot m$.

Figs. 4 and 5 show the results of the graphical analysis. The following main conclusions are reached for the studied case:

- Minimum *WL* happens when *P* = 32 min. By applying the continuous function approach, explained in Sub-Section 4.1 and Eq. (13), to calculate the optimal *P*, the value obtained in that case is 26.7 min, which is very consistent with the results from the case study.
- Milk-run circuit is possible only if 53 min > *P* > 24 min; otherwise, the *mizusumashi's* total work time is higher than work time S.
- Values of *P* higher than the minimum make the work time increase, but smoothly. This implies that it is possible to reduce the surface (by reducing *P*) without too much impact on human productivity. For instance, with *m* = 12 a reduction of 25% in P (from 32 min to 24 min) would increase WL only by 7.2% (from 441.6 to 473.6 min).
- Graphical analysis helps in assigning the number of delivery points (m) (see Fig. 5). For instance, *m* = 12 is feasible, but *m* = 14 is not feasible.

5. Conclusions and future research

This paper presents a method for a single in-plant milk-run design. It has been developed for reducing surface occupation and then achieving minimum *mizusumashi* work time. The 'preloading method' has proven to be a requisite technique for reducing production lines surface and for precise calculation of the number of required coaches. Also, we have found that shortening the replenishment period (*P*) is suitable for minimizing the number of containers at POUs, which in turn reduces the surface needed.

Based on observation and practice, a method for stopping and moving the milk-run train has been described to minimize *mizusumashi* motion and walking time.

This method models the *mizusumashi*'s work time (*WL*) as a function of the replenishment period (*P*), which allows to conclude that there is an optimum *P* that minimizes the *mizusumashi*'s work time.

A graphical analysis of *WL(P)* provided some interesting additional conclusions regarding the relationships between labour and surface productivity:

- If labour productivity is the key cost driver, then supplying at the optimum *P* allows supplying more POUs, thus reducing the total number of *mizusumashis* and trains needed.
- If surface productivity is the key cost driver, then milk run could be conducted with a shorter *P* than the optimum one without too much impact on labour productivity, thus reducing the inventory of production lines.

This method is particularly useful for high-consuming surface value chains, such as supplying high volume parts to a medium or high number of POUs, which is common among industry settings nowadays.

The main limitation of this research is to consider a single milk-run design and to calculate *WL* in a work period (typically one shift) rather than in every loop. As a consequence, variability due to traffic congestions or differences in the number of containers handled in every loop has not been considered. This limitation opens new avenues for further research, namely to:

- Calculate more precisely the coaches configuration based on the Bin Packing Problem in order to model a more accurate $WL_w(P)$.
- Study traffic congestion when more than one milk-run is required.
- Analyse the impact of variability in the milk-run system by means of discrete simulation tools, which can affect the handling time in every single loop.
- Understand the effect of *u* (parts per container) in the consumption of containers per loop.

References

[1] Ohno T (1988) *Toyota Production System: Beyond Large-Scale Production*, Productivity PressCambridge, Massachusetts.
[2] Baudin M (2004) *Lean Logistics: The Nuts and Bolts of Delivering Materials and Goods*, Productivity PressNew York.
[3] Klenk E, Galka S, Günthner WA (2015) Operating Strategies for In-Plant Milk-Run Systems. *IFAC Papers Online* 48(3):1882–1887.
[4] Chee SL, Chong MY, Chin JF (2012) Milk-Run Kanban System for Raw Printed Circuit Board Withdrawal to Surface-Mounted Equipment. *Journal of Industrial Engineering and Management* 5(2):382–405.
[5] Horbal R, Kagan R, Koch T (2008) *Implementing Lean Manufacturing In High-Mix Production Environment*, 257, IFIP (International Federation for Information Processing), 257–267.
[6] Toyota Motor Corporation. *Logistics, Production Part Logistics*, Retrieved September 3, 2019, from: https://www.toyota-global.com/company/history_of_toyota/75years/data/automotive_business/production/logistics/production_parts/index.html.
[7] Schonberger RJ (1982) *Japanese Manufacturing Techniques. Nine Hidden Lessons in Simplicity*, The Free Press.
[8] Ichikawa H (2009) Simulating an Applied Model to Optimize Cell Production and Parts Supply (*mizusumashi*) for Laptop Assembly. In: *Proceedings of the Winter Simulation Conference*.
[9] Nomura J, Takakuwa S (2006) Optimization of a Number of Containers for Assembly Lines: The Fixed-Course Pick-Up System. *International Journal of Simulation Modelling* 5(4):155–156.
[10] Emde S, Fliedner M, Boysen N (2012) Optimally Loading Tow Trains for JIT-Supply of Mixed-Model Assembly Lines. *IIE Transactions* 44:121–135.
[11] Faccio M, Gamberi M, Persona A, Regattieri A, Sgarbossa F (2013) Design and Simulation of Assembly Line Feeding Systems in the Automotive Sector Using Supermarket, Kanbans and Tow Trains: A General Framework. *Journal of Management Control* 24(2):187–208.
[12] Emde S, Gendreau M (2017) Scheduling In-House Transport Vehicles to Feed Parts to Automotive Assembly Lines. *European Journal of Operational Research* 260 (1):255–267.
[13] Korytkowski P, Karkoszka R (2016) Simulation-Based Efficiency Analysis of An In-Plant Milk-Run Operator Under Disturbances. *International Journal of Advanced Manufacturing Technology* 82:827–837.
[14] Kilic HS, Durmusoglu HS, Baskak M (2012) Classification and Modelling for In-Plant Milk-Run Distribution Systems. *International Journal of Advanced Manufacturing Technology* 62:1135–1146.
[15] Gyulaia D, Pfeiffera A, Sobottkab T, Váncza J (2013) Milkrun Vehicle Routing Approach for Shop-floor Logistics. *Procedia CIRP* 7:127–132.
[16] Boonprasurt P, Nanthavani S (2017) Hybrid Genetic Algorithm for Vehicle Routing Problem With Manual Unloading Consideration. *Maejo International Journal of Science and Technology* 11(1):68–80.
[17] Gil Vilda F, Yagüe JA, Suñé A, Jauregui-Becker JM, Wits W (2018) A Geometrical Model for Managing Surface Productivity of U-shaped Assembly Lines. *CIRP Annals - Manufacturing Technology* 67(1):479–482.
[18] Delorme M, Iori M, Martello S (2016) Bin Packing and Cutting Stock Problems: Mathematical Models and Exact Algorithms. *European Journal of Operational Research* 255(1):1–20.
[19] Khairuddin U, Razi NAZM, Abidin MSZ, Yusof R (2020) Smart Packing Simulator for 3D Packing Problem Using Genetic Algorithm. *Journal of Physics: Conference Series* 1447:012041.

2.5. Integration of a collaborative robot in a U-shaped production line: a real case study.

Volviendo al núcleo del diseño desde la persona, este artículo muestra un caso de estudio Lean 4.0: la integración de un Cobot en una célula en U, de nuevo orientado a la productividad de la superficie y, complementariamente, a la productividad humana.

La hipótesis de partida es que un Cobot puede ser incorporado a una Célula en U reduciendo drásticamente las necesidades de espacio respecto a una robotización tradicional.

El caso se desarrolla en dos fases: la primera, la completa desautomatización de la célula y su trasformación en una Célula en U para confirmar la drástica reducción de superficie necesaria, aunque asociada también a una moderada pérdida de productividad humana.

En una segunda fase, la introducción de un Cobot permite mejorar la productividad humana respecto a la robotización tradicional, sin necesidad adicional de superficie.

Más allá de lo expuesto en el caso de estudio, es interesante constatar que sus conclusiones han permitido al grupo industrial donde se implantó la solución estandarizar un concepto de célula cobotizada que está siendo usado extensamente con similares resultados a los mostrados en el caso de estudio, y que podrían ser objeto de un estudio más detallado para generalizar las conclusiones.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 13 (2017) 109–115

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

Manufacturing Engineering Society International Conference 2017, MESIC 2017, 28-30 June 2017, Vigo (Pontevedra), Spain

Integration of a collaborative robot in a U-shaped production line: a real case study

F. Gil-Vilda[a,]*, A. Sune[b], J.A. Yagüe-Fabra[c], C. Crespo[d], H. Serrano[d]

[a]Festo Automation S.A.U., Av. Gran Vía 159, Hospitalet de Llobregat (Barcelona) 08900, Spain
[b]Universitat Politècnica de Catalunya, C/ Colom, 11, Tarrasa (Barcelona) 08222, Spain
[c]I3A – Universidad de Zaragoza, C/ María de Luna, 3, Zaragoza 50018, Spain
[d]Mann+Hummel Ibérica S.A.U., C/ Pertusa, 8, Zaragoza 50197, Spain

Abstract

In lean production environments, such as the U-shaped cells, flexibility is a priority. Therefore, any element that introduces process stiffness is negatively valued. Former studies establish that robotization of tasks in U-shaped cells presents some drawbacks. For instance: it may complicate continuous improvement, prolong changeover time, use a large space or create safety problems for the operators. However, the collaborative robots (CoBots) may change this situation, since they overcome most of the issues previously mentioned. The present study analyses a real case of de-robotization in a traditional assembly line to transform it into a manual U-shaped line. In a second step a CoBot is integrated in the cell replacing one of the workers. This study empirically compares the manufacturing process in these three scenarios. Results in real production conditions show that a U-shape cell assisted by a CoBot increases productivity and reliability while reducing the surface used. These results suggest that collaborative robotics can be integrated in U-shaped production lines and even increase the efficiency of a traditional robotized assembly line.

Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.

Keywords: Lean manufacturing; Collaborative robot; U-shaped production line.

* Corresponding author. Tel.: +34 638 05 17 47
E-mail address: francisco.gil@festo.com

2351-9789 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.
10.1016/j.promfg.2017.09.015

1. Introduction.

One of the main goals of Lean Production Systems is to gain competitiveness by reducing delivery time. This can be achieved by making the system progressively more and more flexible, increasing its capability to produce in one-piece flow and to adapt itself to the customer takt time [1].

In lean production environments, such as U-shaped production lines, flexibility is a priority [2]. Therefore, any element that may introduce process stiffness is negatively valued. Former studies [3] establish that the robotization of tasks in U-shaped cells presents some drawbacks. For instance: it may complicate continuous improvement, prolong changeover time, use large space or create safety problems for operators. However, the collaborative robots (CoBots) may change this situation, since they overcome most of the issues previously mentioned [4]. A collaborative robot is defined as "a robot designed to assist human beings as a guide or assistor in a constrained motion" [5]. However, due to the recent introduction of this technology in industry, there are scarce scientific studies about the integration of collaborative robotics in U-shaped production lines [4].

The goal of this research is to show, through in-depth analysis of a real case, the main advantages and drawbacks of using CoBots in a U-shaped line. Particularly, the studied case shows the evolution of a traditional automated assembly line into a U-shaped that finally incorporated a CoBot to assist the workers on handling tasks. The study of the three designs –one design for each mentioned situation- in real production conditions allows the comparison of different alternatives in the design of production lines. In addition it allows the objective assessment of introducing a CoBot in a U-shaped cell. This study presents the results of the case, its conclusions and possible avenues for future research.

2. Literature review.

U-shaped production lines were conceived as a solution, in lean production environments, for waste elimination and for getting the full utilization of worker's capabilities [6]. Waste removal is usually achieved by the introduction of pull systems, one-piece flow, leveling and jidoka, while fully utilizing workers' capabilities requires a system of respect for people based on minimizing wasted movements, ensuring their safety, and giving them greater responsibility in running and improving their jobs [7].

According to Hyer and Brown [8], a manufacturing cell is characterized by the creation of value flow in which tasks, equipment and operators are closely connected in terms of time, space and information. Transfer and waiting times between operations should be minimized and operations should be in physical proximity to each other, making it easier to move materials, to exchange information and to solve problems. In order to keep the value flow and minimize operators' movements, using large machines results in serious disadvantages. Another aspect that makes U-shaped cell design especially interesting is the capability of adaptation to the customer takt time. This can be achieved by working one-piece flow and varying its cycle time [9]. Therefore, introducing automatic systems is usually discarded because it may interfere the operators' working cycle, enlarge the changeover time or interrupt the production flow, e.g. operating in batches. Eventually, although the idea of combining human flexibility with robot efficiency is attractive, safety issues due to physical proximity of people and robots may be taken into consideration. Traditional robot restrictions make unfeasible a tight collaboration among people and robots sharing the same working area [3]. For all these reasons, some companies started to cut out automation of some operations when transforming their production lines into U-shaped cells.

In spite of the mentioned difficulties, the recent appearance of collaborative robots (CoBots) opens new opportunities for their utilization in industrial environments. A collaborative robot may be defined as "a robot designed to assist human beings as a guide or assistor in a constrained motion" [5]. Cobots are intended for direct interaction with a human worker [10]. Collaborative robots features allow operators to share the working area with no physical barriers between them [3]. In addition, cobots have generally been identified as being ideal for manufacturers with more variants and smaller lot sizes [11], which is an intrinsic feature of lean production systems. In conclusion, it becomes interesting to carry out an in-depth study on the integration of cobos into U-shaped cells.

3. Case study description.

This Case Study presents a real execution developed in a Tier 1 supplier for the main car builders in Europe. The manufacturing plant is currently involved in a transformation project from a “Push Production System” to a “Pull Production System” with an additional Industry 4.0 strategy.

The studied production line is dedicated to the manufacturing of a component family for the automotive industry. Products are composed of a plastic body - formed by three welded parts – assembled with a filtering element. Finally a number of additional components, purchased to external suppliers, are also assembled to the body.

3.1. Initial situation: semi-automated line based on a traditional robot.

The product family was originally manufactured in a semi-automatic standard line managed by a monthly planning system. The facility consisted of a robotic cage fed by conveyors plus two isolated manual stations. The line was directly connected to two injection machines by conveyors. The general standard layout of this line is shown in Fig. 1.

At the starting point of the case study a new product family replaced the previous one and it was produced at the studied manufacturing line.

Fig. 1. Standard layout for initial semi-automated production line.

3.2. Intermediate situation: U-shaped assembly line without robot.

The lean transformation project introduced new flexibility and adaptability requirements for the customer takt time, so that the manual assembly operations were disassociated from the injection machines through a kanban. Due to the product features [12], the line was redesigned to a one-piece flow process in a U-shaped production line working in “fixed stations” mode [9], synchronizing man-machine times.

Due to this new cell configuration, introducing a traditional robot into the working space was not possible and the production line was de-robotized, as can be seen in Fig. 2 layout.

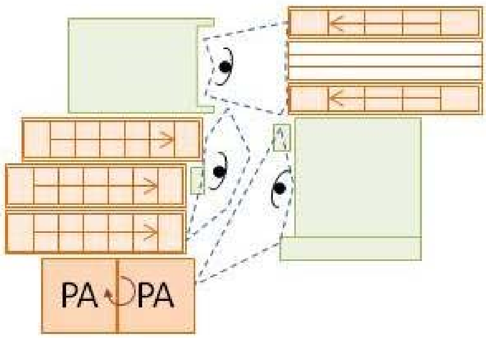


Fig. 2. Standard layout for de-robotized U-shaped assembly line.

3.3. Final situation: U-shaped assembly line with cobot.

Due to needed improvements in labor productivity, new flexible automation options were analyzed according to the Industry 4.0 strategy [13] that the company was addressing. The new possibilities that collaborative robots offer were explored and finally it was agreed to integrate a cobot sharing the working space in the U-shaped cell.

No prior research on the integration of a cobot inside the working area of a U-shaped cell have been found so far, so this might be the first published case of such integration, shown in Fig. 3.

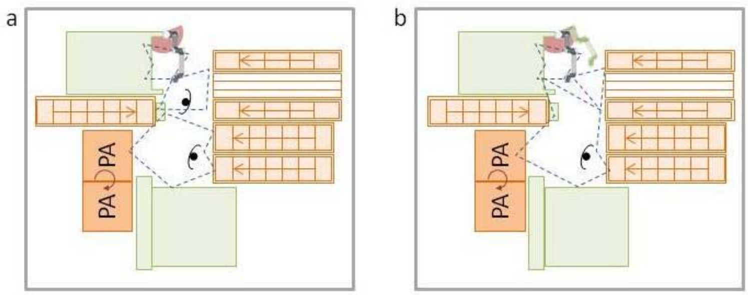


Fig. 3. U-shaped assembly line working in fixed stations with a cobot (a) 2 operators; (b) 1 operator.

4. Methodology and results.

A longitudinal single case studyn empirical methodology has been used in order to empirically measure the effectiveness of each solution along time. Effectiveness Key Process Indicators (KPIs) have been defined aligned with the lean transformation project objectives. These KPIs have been measured for each solution. Additionally the strategy to achieve the KPIs targets has been identified and described.

KPIs defined to measure the effectiveness of the different solutions are described below:

- Labor productivity: number of good units divided by man-hour (units/hour/#operators).
- Surface: Total surface occupied by operators, machines and materials (m2).
- Surface productivity: Actual capacity divided by production surface (units/hour/m2).
- Performance: % over standard labor productivity.

4.1. Initial situation.

As mentioned before the initial situation was based on a fixed cycle time production, manual handling by operators in isolated and dedicated stations, some operations were carried out by a traditional robot and parts were moved through connecting conveyors.

In such a situation the strategy followed to increase labor productivity was based on:

- Maximum reduction of the cycle time for a maximum saturation of workers and machines.
- Adaptation to the demand variation by means of large batch production in discontinuous production periods.
- No strategy to raise space productivity was considered at this stage.

The KPIs for this initial situation are shown in Table 1.

Table 1. KPIs for the initial situation.

KPI	Value
Labor Productivity (u/h/o)	100
Surface (m2)	170
Surface Productivity (u/h/m2)	0,61
Performance (%)	75%

4.2. Intermediate situation.

This situation was characterized by the fact that the production line was de-robotized in order to produce with variable cycle time and increased flexibility. As a result, a U-shaped production cell with variable cycle time, depending on the customer takt time, was built. In this case handling was fully manual.

In such a situation the strategy followed to increase labor productivity was based on:

- Man-machine synchronization to avoid operators' idle times.
- Continuous production permanently adapted to the customer takt time.
- Adaptation to the demand variation by changing the number of operators (from 1 to 3).

In this case the strategy to raise space productivity was based on:

- Compact U-shaped configuration.
- Decrease of in-line supplies by means of a frequent mikrun.

The KPIs for this intermediate situation are shown in Table 2.

Table 2. KPIs for the intermediate situation.

KPI	Value
Labor Productivity (u/h/o)	78
Surface (m2)	45
Surface Productivity (u/h/m2)	1,98
Performance (%)	92%

4.3. Final situation.

This situation was characterized by the inclusion of a collaborative robot partially replacing one operator. As in the intermediate situation, a U-shaped production cell with variable cycle time, depending on the customer takt time was used. Regarding handling, loading and unloading tasks at one of the machines was carried out by the cobot.

In this final situation the strategy followed to increase labor productivity was based on:

- Man-machine synchronization to avoid operators' idle time.
- Continuous production permanently adapted to the customer takt time.
- Adaptation to the demand variation by changing the number of operators (from 1 to 2).

The strategy to raise space productivity was based on:

- Compact U-shaped configuration.
- Decrease of space needed in the collaborative robot area.
- Decrease of in-line supplies by means of a frequent milkrun.

The KPIs for the final situation are shown in Table 3.

Table 3. KPIs for the final situation.

KPI	Value
Labor Productivity (u/h/o)	118
Surface (m2)	45
Surface Productivity (u/h/m2)	2,59
Performance (%)	92%

4.4. Discussion.

A summary of the KPIs evolution is shown in Table 4:

Table 4. Comparative results.

KPI	Initial	Intemediate	Final
Labor Productivity (u/h/o)	100	78	118
Surface (m2)	170	45	45
Surface Productivity (u/h/m2)	0,61	1,98	2,59
Performance (%)	75%	92%	92%

Fig. 4 shows that labor productivity decreased by 22% when the robotized line was transformed into a manual U-shaped cell. The inclusion of the cobot in the production cell increased productivity by 18% with respect to the initial baseline.

Surface requirements decreased from 170 m2 to 45 m2 due to the cell layout. The inclusion of the cobot did not require any additional space due to its collaborative features, which allowed its integration into the space of the U-shaped cell.

Surface productivity increased by 225% due to the U-shaped layout. The inclusion of the cobot did not modify the surface requirements but increased the surface productivity due to higher capacity.

The facility performance improved from 75% to 92% due to the simplification of the robotic system, saving maintenance and set-up resources.

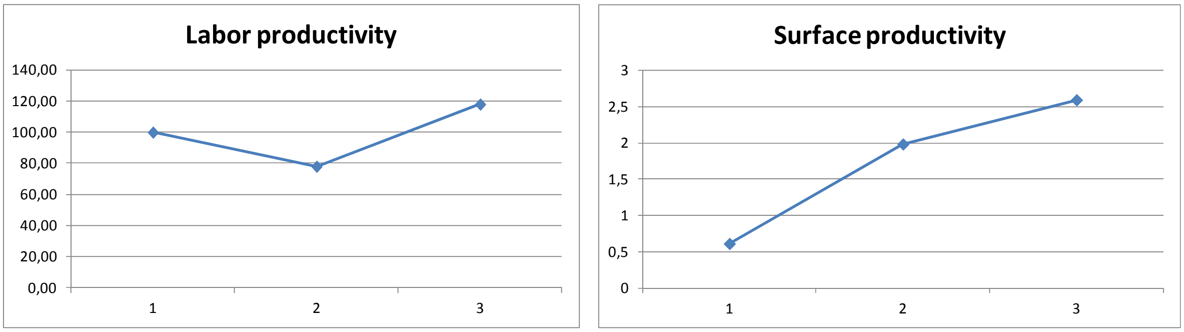


Fig. 4. KPIs evolution.

5. Conclusions and future research.

This research shows the evolution of a manual U-shaped cell in comparison to a traditional robotized line. In addition, it shows that a collaborative robot may be integrated in the working area of a U-shaped assembly cell under safe conditions with no need of extra space and, therefore, keeping the high space productivity of a manual U-shaped cell.

The results presented here, under real production conditions, show that, in a U-shaped cell, a cobot collaborating with human operators may raise labor productivity. These results were even better than a traditional robotized line.

Collaborative robotics opens a new field for automation which was not possible so far: combining the surface productivity achieved by using U-shaped cells with the raise of labor productivity by automating handling tasks.

Future research in this field may focus on the generalization of these results. A potential field would be the analysis of geometrical configurations for U-shaped cells willing to integrate cobots for additional space reductions. Another interesting avenue for future research is the study of emotional implications for operators when collaborating with cobots in the working area.

Acknowledgements

Authors want to show their acknowledgement to Mann+Hummel and Festo for providing the necessary resources to carry out this work.

References

[1] T.A. Saurin, G.A. Marodin, J.L.D. Ribeiro, Int. J. Prod. Res. 49 (2011) 3211-3230.
[2] S.L. Hunter, J.T. Black, J. Adv. Manuf. Syst. 6 (2007) 129-144.
[3] J.T.C. Tan, F. Duan, R. Kato, T. Arai, Adv. Robot. 24 (2010) 839-860.
[4] A.M. Djuric, J.L. Rickli, R.J. Urbanic, SAE Int. J. Mater. Manuf. 9 (2016) 457-464.
[5] Z.M. Bi, S.Y.T. Lang, L. Wang, J. Intell. Manuf. 19 (2008) 715-722.
[6] J.K. Liker, The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer, McGraw-Hill, New York, 2004.
[7] E. Lander, J.K. Liker, Int. J. Prod. Res. 45 (2007) 3681–3698.
[8] N.L. Hyer, K.A. Brown, J. Oper. Manag. 17 (1999) 557–574.
[9] J. Miltenburg, IIE Trans. 33 (2001) 303-321.
[10] M. Peshkin, J.E. Colgate, Ind. Rob. 26 (1999) 335-341.
[11] J. Krüger, T.K. Lien, A. Verl, CIRP Ann. Technol. 58 (2009) 628–646.
[12] G.R. Aase, J.R. Olson, M.J. Schniederjans, Eur. J. Oper. Res. 156 (2004) 698–711.
[13] D. Kolberg, D. Zühlke, IFAC-PapersOnLine, 48 (2015) 1870-1875.

3. Discusión de los artículos publicados y sus resultados.

Esta tesis se presenta en la modalidad de compendio de publicaciones.

A continuación, se presenta con más detalle una discusión de los resultados de los artículos y sus mayores aportaciones en el orden temático coherente (no en el cronológico), así como las relaciones que los unen.

3.1. From Lean Production to Lean 4.0: A systematic literature review with a historical perspective.

Durante las últimas décadas y como consecuencia del incremento de la competitividad de los mercados, el término "lean" se ha propagado ampliamente como una forma de gestión adecuada para mejorar la productividad, la calidad y el *lead time* tanto en organizaciones industriales como de servicios. Su sobreuso y progresiva asociación a diferentes palabras complementarias ha creado confusión y equívocos tanto en el ámbito académico como industrial.

El trabajo tiene como objetivo, a través de una Revisión Sistemática de la Literatura que sigue la propuesta metodológica de Denyer et al. (2009), indagar y aclarar el origen, la evolución y la diversificación del concepto "lean". Para ello analiza 4.962 artículos académicos provenientes de las bases de datos Web of Science y Scopus (todos ellos contienen "lean" en su título, y fueron publicados entre 1988 y 2020) y 20 libros seminales abundantemente citados en la literatura, basados en la lista propuesta por Holweg (2007).

La primera conclusión de este trabajo es que el término "lean" fue utilizado por primera vez en 1988 por J.F. Krafcik en su artículo *Triunf of the Lean Production System* (Krafcik, 1988) dentro del International Motor Vehicle Program del MIT. Parece claro que el termino fue acuñado como un sobrenombre para referirse al Sistema de Producción Toyota sin nombrar a Toyota, que no participaba en el IMVP, como sugiere New (2007).

Los orígenes el Sistema de Producción Toyota se remontan a los años 50 y hay un consenso general en que Taiichi Ohno fue su promotor y líder dentro de Toyota. Así lo reconoce el primer artículo en inglés que se conoce, presentado en 1977 por discípulos de Ohno: *Toyota Production System and Kanban System. Materialization of Just-In-Time and Respect-for-human System* (Sugimori et al., 1977).

Entre 1977 y 1988, Los primeros autores japoneses que investigaron el *Toyota Prodution System* (Monden, 1983; Shingo, 1981) se refieren a él por su nombre. Sin embargo, los primeros autores estadounidenses propusieron diferentes sobrenombres al TPS como *Stockless Production* o *JIT production* (Schonberger, 1982), *Value-added manufacturing* (Hall, 1983), *continuous improvement manufacturing* (Hall, 1987), *fragile production* (Shimada & MacDuffie, 1986).

Después del éxito del *best seller* "La máquina que cambio el mundo" (Womack et al., 1990) escrito por los directores del IMVP, el término "*Lean Production*" se impuso e hizo caer en el olvido cualquiera de los anteriores. La "producción lean" es presentada en contraposición a la "producción en masa" en un libro más orientado al *bechmarking* que a la descripción del sistema. Quizá primer síntoma y causa de la pérdida de enfoque holístico durante la década de los 90 como sugieren Sha et al. (Shah & Ward, 2007).

La segunda conclusión, analizado la métrica artículos/año (ver figura 3.1), es que el interés académico por el "Lean" se mantuvo bastante estable entre los años 1990 y 2005 y muy restringido al mundo industrial bajo las denominaciones "*lean manufacturing*" y "*lean production*". A la vez que se inició una diversificación hacia otros ámbitos añadiendo "apellidos" al término. A partir del 2004, sin embargo, el interés se disparó, en cierta medida debido a la aparición del concepto "*Lean Six Sigma*" que ha merecido creciente atención desde el año 2005, aplicado tanto a la industria como a los servicios.

El articulo propone cuatro mecanismos que explican la diversificación del concepto "lean" a lo largo del tiempo:

- Expansión: el concepto se extiende dentro del campo de la producción.
- Transferencia: el concepto se extiende más allá del campo de las operaciones.
- Concreción: el concepto se focaliza en un sector particular.
- Combinación: el concepto se combina con otros conceptos.

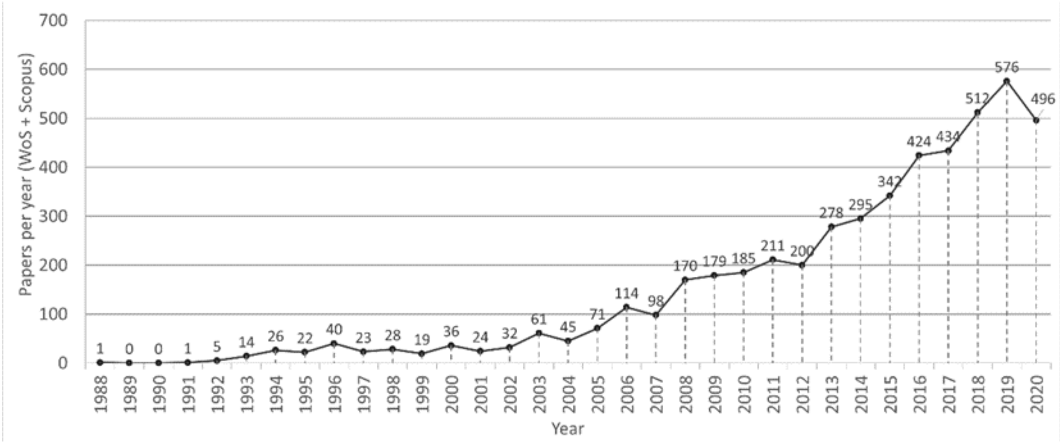


Figura 3.1. *Evolución cronológica de los artículos/año con "lean" en el título.*

A través de estos mecanismos o su combinación se puede explicar la evolución del concepto a lo largo del tiempo mediante los 17 especificadores o "apellidos" identificados para complementar el término "Lean".

- *Lean Production* (Krafcik, 1988) y *Lean Manufacturing* (Powell, 1993) pueden considerarse como los conceptos originales o sobrenombres del TPS. La literatura los usa indistintamente para referirse al entorno productivo.
- *Lean Logistics* (Fynes & Ennis, 1994), *Lean Supply* (Lamming, 1996) o *Lean Supply Chain* (Ó hUallacháin & Wasserman, 1999), *Lean Product* (Karlsson & Åhlström, 1996) son una expansión del término más allá de la producción, a la gestión de la cadena de suministro y el diseño de producto respectivamente.
- *Lean Management* (Petrovic & Zsifkovits, 1994), *Lean Enterprise* (Womack & Jones, 1996a), *Lean Thinking* (Womack & Jones, 1996b), son una transferencia de la idea "lean" para llevarla a un nivel más conceptual, de forma que pueda aplicarse más allá del campo estricto de las operaciones industriales.
- *Lean Construction* (Koskela, 1994) es una concreción al sector construcción.
- *Lean Service* (Bowen & Youngdahl, 1998) *Lean Office* (Locher, 2011), *Lean Healthcare* (Portioli-Staudacher, 2008), *Lean Hospital* (Graban, 2009) son una transferencia más allá de la producción, y una concreción a sectores específicos (servicios, salud y hospitales).

- *Lean and Green* (Florida, 1996), *Lean Six Sigma* (Furterer & Elshennawy, 2005), *Lean Startup* (Blank, 2013) y *Lean 4.0* (Metternich et al., 2017) son una combinación con otros conceptos para hacer evolucionar la metodología.

Como conclusión, el artículo presenta la evolución histórica y los mecanismos de diversificación del término Lean desde su origen hasta la actualidad. Muestra cómo, más allá de su origen en el ámbito de las operaciones, sus principios y herramientas se pueden adaptar a otros entornos complejos, competitivos y cambiantes.

El trabajo de desarrollo del artículo puso de relevancia también el concepto seminal "*respect-for-human*" que ha sido ampliado en la revisión de la literatura de esta memoria y que sirve de base para el siguiente trabajo centrado en la aplicación "lean" en el ámbito industrial.

3.2. Person-based design: A human-centered approach for lean factory design.

En un entorno cada vez más competitivo y complejo, contar con un sistema de organización que se mantenga permanentemente alineado con el mercado se convierte en una ventaja competitiva.

Para las organizaciones industriales es un desafío construir sistemas de producción muy eficientes que integren a las personas mejorando sus capacidades y habilidades, pero a la vez respetando sus aspiraciones como individuos; especialmente si son muy intensivas en trabajo humano.

El artículo propone una visión holística de los sistemas de producción como sistemas socio-técnicos (Bidanda et al., 2005) como un conjunto integrado de principios, herramientas y métodos en constante interacción con las personas (ver Figura 3.2).

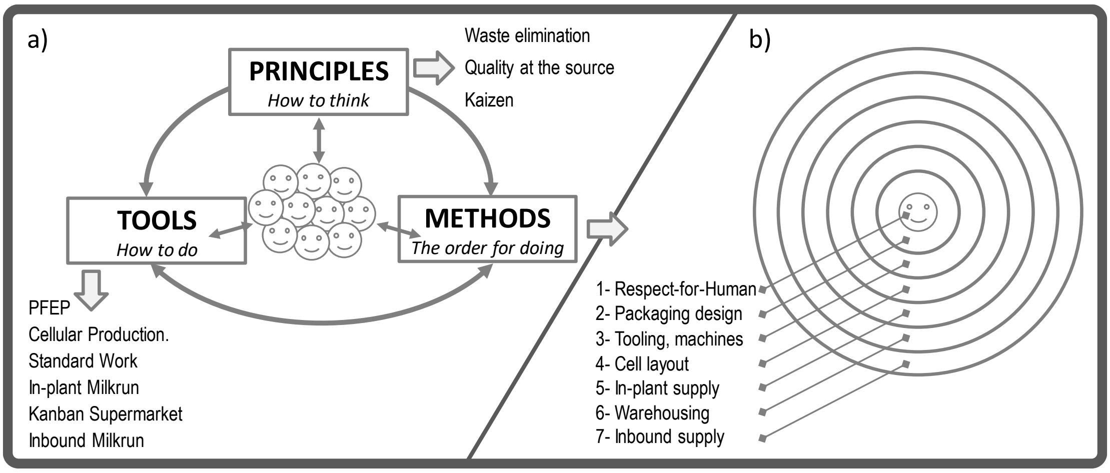


***Figura 3.2.** a) Lean como un Sistema. b) Diseño desde la persona.*

A continuación, propone un método específico para diseñar fábricas altamente eficientes compatibles con el respeto a las personas.

Para ello, propone un proceso secuencial de diseño (*Person-Based Design*) en siete capas concéntricas que empiezan por un núcleo central "respeto por las personas" y continúa hacia afuera, como si de una cebolla se tratase. Estas siete capas incluyen el diseño de los embalajes, el diseño de las herramientas y las máquinas, el diseño de la célula de producción, el diseño de la logística interna, el diseño del almacén y el diseño de la cadena de aprovisionamiento. Con una única regla de diseño: conseguir la máxima eficiencia de cada capa siempre y cuando una decisión de diseño nunca perjudique la eficiencia de las capas que contiene.

Para terminar, el artículo presenta un caso real en el que la metodología se aplicó para rediseñar un área de producción donde se fabricaban cinco subconjuntos que suministraban a una línea de producción a una cadencia de 30 s/unidad. Se consiguió con ello una reducción de la superficie utilizada a la mitad, un aumento de productividad humana del 18% y una reducción del stock en curso de 13 horas a 2 horas (tabla 3.1 y figura 3.3).

Tabla 3.1. *Resumen de los parámetros analizados y su porcentaje de mejora.*

KPI	Antes	Después	% mejora
Stock en proceso (h)	13	2	550%
Superficie (m^2)	102.6	57	70%
Productividad humana (u/h/p) (incluido suministro de materiales)	6.7	7.9	18%

Como conclusión, este articulo presenta los Sistemas de Producción Lean como un sistema socio-técnico y ofrece un modelo de pensamiento sencillo y útil para entender las interrelaciones y algunos factores de éxito en su implantación.

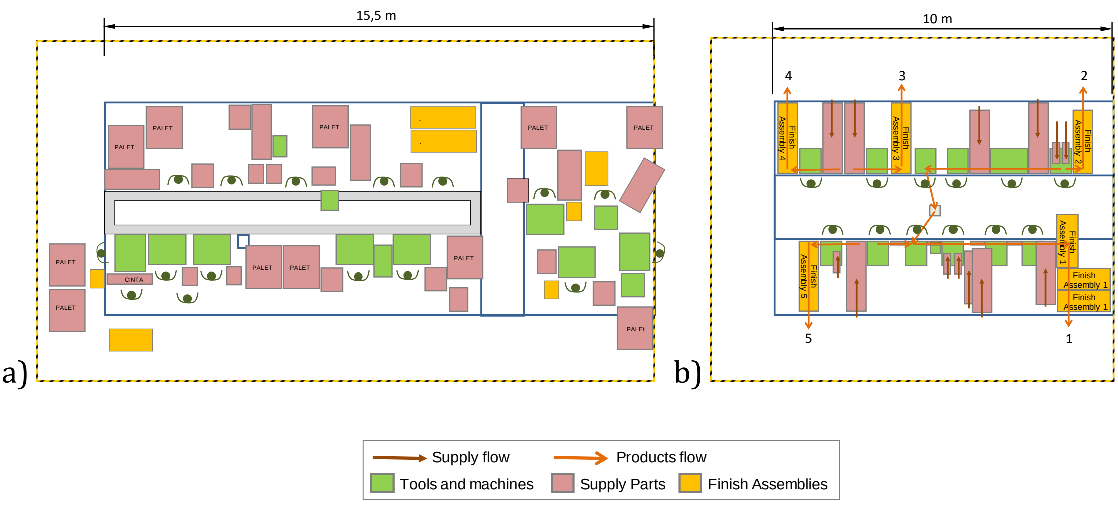


Figura 3.3. *Optimización de la superficie: a) Situación inicial antes de Diseño Desde la Persona. B) Célula en "=" mostrando los 5 flujos de productos.*

Este trabajo presentó, por primera, vez el método “diseño desde la persona” que es uno de los hilos conductores de esta tesis y dio una lógica de diseño para conseguir sistemas de producción eficientes asegurando el respeto a las personas.

Una vez introducido el método y más allá de sus resultados positivos en un caso concreto, requiere un desarrollado metodológicamente que lo haga útil como herramienta de diseño. El siguiente trabajo, en consecuencia, se basa en desarrollar las 4 primeras capas para un diseño industrial basado en Células en U cómodas, ergonómicas y compactas.

3.3. A geometrical model for managing surface productivity of U-shaped assembly lines.

Este artículo profundiza en el diseño de las primeras capas del método *Person-Based Design* centrándose en el diseño de Células de Producción en U (*U-shaped assembly Lines, U-SAL*) con el enfoque de la gestión y mejora de la productividad del espacio.

La revisión de la literatura muestra la evolución histórica de las U-SAL desde su primera mención por Taiichi Ohno, que ensayó una en 1945 (Taiichi Ohno, 1988). Como curiosidad histórica, Ohno en una primera traducción de su libro describe las células en U como "máquinas ordenadas con forma del símbolo "=".

La literatura revisada también muestra el interés académico por la productividad humana de las U-SALs (Aase et al., 2004; Miltenburg, 2001), pero apenas muestra atención por la productividad del espacio.

Con una metodología inductiva, el artículo analiza cinco células en U reales buscando un modelo geométrico que permita un mejor aprovechamiento del espacio (figura 3-4) para concluir que la mejor opción es, precisamente, la forma "=" propuesta por Ohno (1988).

Los diferentes factores que influyen en el consumo de espacio (Tabla 3.2) son analizados y se define un modelo matemático simplificado para calcular la superficie necesaria por una célula bajo la premisa "mejor imposible" (*as good as it gets*), es decir, que proporcione la mínima superficie necesaria posible. Por lo tanto, se obtiene así una información muy útil para cálculos minimalistas y poder descartar opciones simplemente insuficientes.

Las simplificaciones introducidas hacen que el modelo sea más preciso con productos de tamaño mediano.

Tabla 3.2. *Parámetros que influyen en las necesidades de superficie*

	Factor	Conexión y notación
Mercado	Demanda del cliente	La Demanda del cliente (D) define el Takt Time (TT) que influencia el velocidad de producción (Q).
Producto	Complejidad	Define el Tiempo de Ensamblaje Manual (T_{ma}). Define el número de componentes a disponer en el puesto de trabajo.
	Tamaño	Define la mínima superficie en la estación de trabajo para manipular el producto.
Proceso	Tecnología	Define el tamaño de las máquinas. Define el Tiempo de ensamblaje Automático (T_{au}).
	Proceso de Suministro a línea	Define el Ciclo de Aprovisionamiento (C_f) y por tanto la cantidad de componentes en el puesto de trabajo.
	Procesos de Producción	Define la velocidad de la línea (Q) y el Tiempo de Ciclo (T_C).

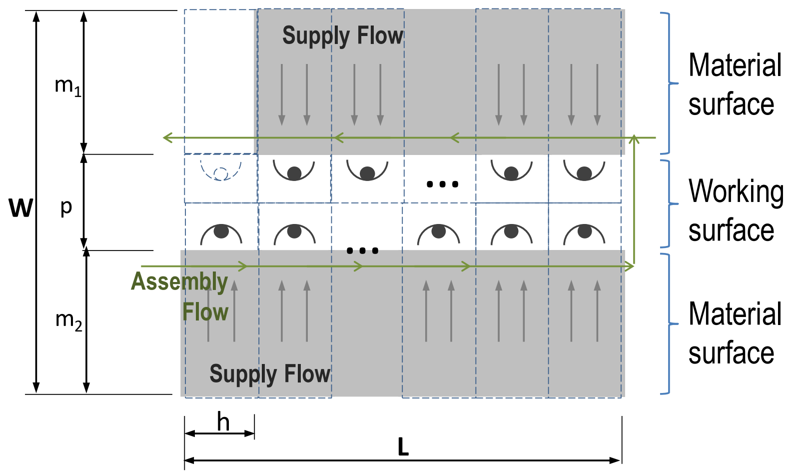


Figura 3.4. *Topología de una célula de producción con forma de "=".*

El modelo matemático presenta algunas conclusiones muy interesantes:

- La superficie necesaria para una célula configurada en "=" tiene una relación cuadrática con la velocidad de producción. Lo que implica que sobre acelerar sin necesidad el ritmo de producción es muy ineficiente en consumo de espacio (fórmula 1).

- Una vez que el producto y la velocidad de producción quedan definidas, la superficie puede reducirse actuando sobre el ciclo de aprovisionamiento. Menor ciclo de aprovisionamiento implica un menor espacio requerido.
- No hay un óptimo matemático para la superficie respecto al tiempo de ciclo de la línea, sin embargo, sí hay ciertos tiempos de ciclo que optimizan localmente la superficie.

$$S = \left(p + \delta \cdot \frac{C_f}{T_c}\right) \cdot \left\lceil \frac{T_{ma}}{2 \cdot T_c} \right\rceil \cdot h = \left(p + \delta \cdot C_f \cdot Q\right) \cdot \left\lceil \frac{T_{ma} \cdot Q}{2} \right\rceil \cdot h \tag{1}$$

Como conclusión, el modelo presentado para la configuración de una Célula en U es muy útil para el diseño del *layout* del sistema de producción por los siguientes motivos:

- Permite al diseñador un cálculo rápido de la superficie necesaria bajo la premisa "mejor imposible" muy útil para descartar soluciones iniciales imposibles.
- El modelo ofrece al diseñador un método para adaptar la superficie de la célula a la disponibilidad de superficie a partir de dos parámetros: el tiempo ciclo de la célula y, sobre todo, el ciclo de aprovisionamiento.
- El modelo es más exacto cuanto mayor es el tamaño del producto fabricado, situación en la que es especialmente relevante la necesidad de superficie industrial.

Si bien el modelo propuesto ofrece unas conclusiones muy interesantes, estas se restringen a la superficie exclusivamente ocupada por la célula. No tiene en cuenta la superficie necesaria para el/los pasillo/s que la circunvalan, necesarios para permitir el aprovisionamiento. Este hecho unido a la influencia que el ciclo de aprovisionamiento tiene en el espacio ocupado (debido a la mayor o menor acumulación de material en la célula para asegurar su funcionamiento ininterrumpido) conduce a la necesidad de plantear una metodología de diseño para la siguiente capa del modelo (suministro interno). Este es el objeto principal del siguiente artículo.

3.4. An in-plant milk-run design method for improving surface occupation and optimizing mizusumashi work time

Este artículo es consecuencia directa del anterior. Dado que un mecanismo para disminuir la ocupación de espacio de una Célula en U es reducir el ciclo de aprovisionamiento, pero reducir el ciclo de aprovisionamiento implica un mayor número de viajes almacén-célula-almacén; la investigación se ha dirigido a buscar un método de diseño para los circuitos *milk-run* que optimice, primero la superficie y después la carga de trabajo de su conductor (denominado en el artículo *Mizusumashi*), tal y como se explica a continuación (figura 3.5.).

Los circuitos *milk-run* de aprovisionamiento interno fueron introducidos por Toyota en 1977 (con el nombre de *Mizusumashi*) como un ciclo de aprovisionamiento multi-parada para suministrar una o varias líneas de producción de forma frecuente y en cantidades pequeñas. *Milk-run* es, en consecuencia, un sistema de aprovisionamiento para producción en serie corta y variada especialmente eficiente (Gil Vilda et al., 2020).

Como se ha expuesto en el artículo anterior, utilizar circuitos *milk-run* para el aprovisionamiento interno permite modelizar la necesidad de superficie de la célula de producción a través del ciclo de aprovisionamiento, que es una variable independiente que puede definir el diseñador.

Este trabajo propone un método de diseño original basado, en primer lugar, en reducir la ocupación de superficie (tanto de la célula de producción como de los pasillos por los que circula el *milk-run*) y después optimizar la carga de trabajo del conductor.

El método planteado presenta como contrapartida un sobredimensionamiento de la longitud del tren debido a dos efectos:

- Para minimizar la superficie de la célula se propone la precarga del tren con el máximo número de contenedores que la línea puede llegar a consumir en un ciclo de aprovisionamiento; de esta forma en la línea sólo debe tener materiales ocupando espacio para un ciclo de autonomía. Como contrapartida, se sobredimensiona el número de contenedores a transportar (el tren es en parte un almacén rodante que no ocupa espacio dado que circula por los pasillos) y, en consecuencia, sobredimensiona el número de vagones y la longitud del tren.

- El diseño de vagones estrechos propuesto para reducir la anchura del pasillo de circulación provoca también un alargamiento del tren (figura 3.5).

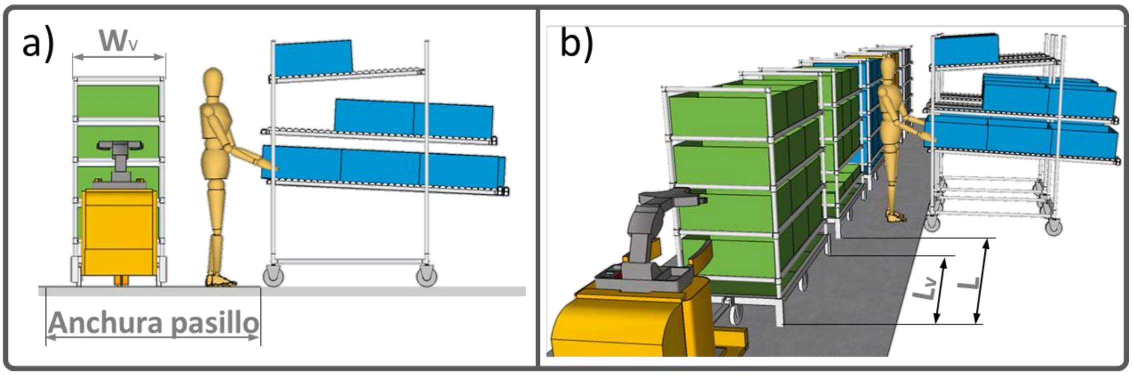


Figura 3.5. *Milk-run suministrando a un Punto de Consumo (POU, Point Of Use).*

Considerando que la longitud del tren es la que el conductor del *milk-run* debe recorrer para abastecer los puestos (dado que debe desplazarse desde la máquina a los diferentes vagones, figura 3.6) se observan dos efectos contrapuestos sobre la carga de trabajo del conductor: un menor ciclo de aprovisionamiento implica menor tiempo de recorrido máquina-vagones-máquina (al ser el tren más corto), pero mayor tiempo de conducción. Cabe entonces intuir un Ciclo de Aprovisionamiento óptimo que minimice la carga de trabajo del conductor.

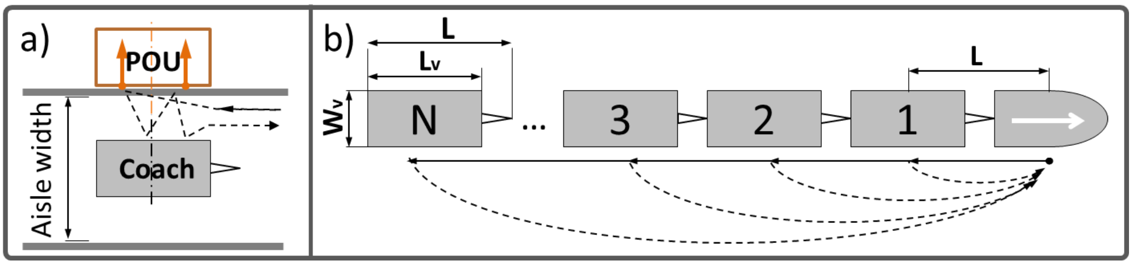


Figura 3.6. *Recorridos del conductor máquina-vagones-maquina a lo largo de un periodo completo de Aprovisionamiento.*

Considerando que la carga de trabajo del conductor se compone del tiempo conduciendo, más el tiempo manipulando cajas, más el tiempo paseando máquina-vagones-máquina, el artículo propone una formulación matemática que convierte la carga de trabajo del conductor en una función del ciclo de aprovisionamiento (y de otros parámetros relevantes).

Como aportación relevante, la observación empírica de *milk-runs* en operación inspiró una modelización simplificada pero realista del tiempo de paseos del conductor máquina-vagones-máquina como una simple progresión aritmética (Figura 3.6b).

La función descrita es discreta y tiene un mínimo que se puede calcular gráficamente.

Adicionalmente una aproximación continua permite calcular, por derivación, un ciclo de aprovisionamiento que minimiza la carga de trabajo resultando en la fórmula (2).

$$P = \frac{C_t \cdot M \cdot u}{n} \sqrt{\frac{T_t}{2 \cdot L \cdot T_W}} \tag{2}$$

Los cálculos realizados con el modelo matemático han arrojado resultados del mismo orden de magnitud que los *milk-runs* empleados en empresas reales, diseñados en base a la experiencia.

Como conclusión, este artículo proporciona un método de diseño para los circuitos *milk-run* orientado a minimizar el uso del espacio industrial empleado tanto por las líneas de producción como por sus pasillos de aprovisionamiento. Este método resulta muy útil en entornos industriales con un alto coste del suelo, especialmente si se fabrican productos muy voluminosos.

En este punto, la unión de un método de diseño para la Célula en U y su circuito milk-run de aprovisionamiento (orientados ambos a la reducción del espacio ocupado), crea un conjunto que reproducido puede dar lugar a múltiples configuraciones de la planta productiva (en función de la geometría disponible) muy compactas. A modo de idea introductoria de un futuro desarrollo se presenta en la figura 3.7 un posible layout ideal para una planta de ensamblaje compacta y optimizada en el espacio.

El desarrollo metodológico del modelo de diseño "Diseño desde la Persona" objeto de esta tesis se detiene en este punto, dejando abierta dos claras líneas de trabajo para seguir avanzando en el diseño de fábricas compactas y eficientes:

- Cómo generar layouts de planta eficientes en el uso del espacio y, en el caso de que sean necesarios varios milk-runs, que no generen derroches de espera en forma de "atascos" debidos a las interacciones entre los milk-runs.
- Cómo generar un diseño de almacén compacto orientado a una eficiencia de los milk-runs.

Complementariamente a lo anterior, el último artículo de esta tesis introduce, en el ámbito Lean 4.0., cómo el uso de una tecnología Industria 4.0. puede integrarse en el Diseño Desde la persona.

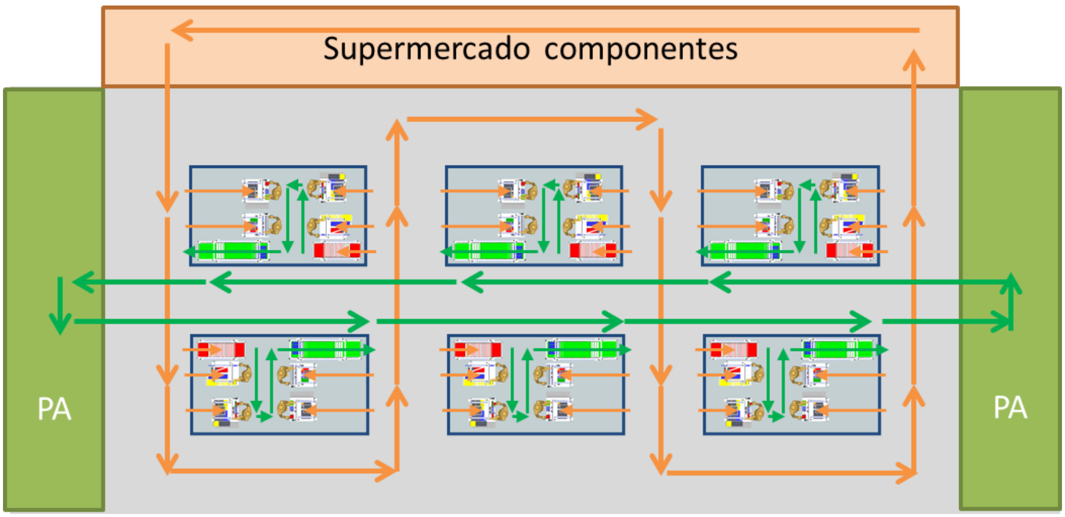


***Figura 3.7**. Propuesta de layout industrial compacto.*

3.5. Integration of a collaborative robot in a U-shaped production line: a real case study.

Este trabajo presenta un caso de estudio real en el ámbito recientemente denominado "*Lean 4.0*". Investiga, en particular, la incorporación de la robótica colaborativa a un Sistema de Producción Lean a través de la descripción, por primera vez en la literatura académica, de la incorporación de un Robot Colaborativo (Cobot) dentro de una Célula en U.

Las células en U son la mejor expresión del flujo continuo unidad por unidad en un espacio compacto. Las células en U buscan además flexibilidad (producción en series cortas) y adaptabilidad (posibilidad de variar la capacidad sin pérdida de productividad humana).

En este entorno, la robotización tradicional supone graves inconvenientes debido a la superficie necesaria y a la inflexibilidad que introduce cualquier automatización. De esta forma, hasta la fecha, células en U y robotización eran conceptos en la práctica poco compatibles.

Sin embargo, la irrupción de la robótica colaborativa ha cambiado este paradigma, permitiendo integrar robots que pueden trabajar en colaboración con los operarios, aunque a velocidades bajas.

El caso de estudio describe la transición de una línea de producción con automatización basada en un robot tradicional (figura 3.9) a una célula en U con un Cobot integrado (figura 3.10B). La motivación para realizar este cambio fue, dentro de un proceso de transformación Lean de la planta, la falta de superficie disponible.

En una primera fase la célula se des-automatizó completamente para ser reemplazada por una Célula en U con un importante ahorro de superficie, pero una pérdida de productividad humana (figura 3.10 A).

En un segundo paso se introdujo un Cobot en el interior de la célula reemplazando parcialmente a una persona. El Cobot asumió una serie de tareas de bajo valor añadido e incómodas para las personas, lo que hizo que fuera bien aceptado por el equipo humano.

El resultado fue el paso de una línea automatizada programada en flujo "*push*" que operaba a la máxima velocidad posible para saturar los puestos humanos aislados, a una célula en U operando en flujo "*pull*" que variaba su velocidad para adaptarse al *Takt Time* del cliente, mejorando la productividad humana con la integración de un Cobot.

El estudio analiza tanto la superficie ocupada como la productividad humana para mostrar que (ver figura 3.8):

- La superficie ocupada se redujo de 170m^2 a 45 m^2.
- La productividad humana aumentó un 18%.

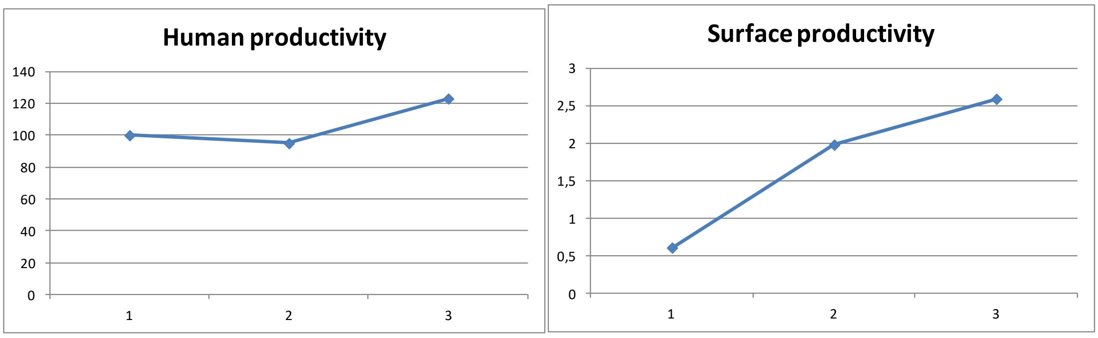


Figura 3.8. *Evolución del indicador de productividad humana y de la superficie.*

Como conclusión, se presenta un primer caso de estudio (que sería interesante ampliar) que muestra un ejemplo de aplicación de una tecnología propia de la Industria 4.0 (automatización mediante Cobot) que, a diferencia de una robotización tradicional, permite reducir el derroche sin disminuir la flexibilidad. Un ejemplo de lo que debería buscar el concepto *Lean 4.0*, recientemente introducido en la literatura científica.

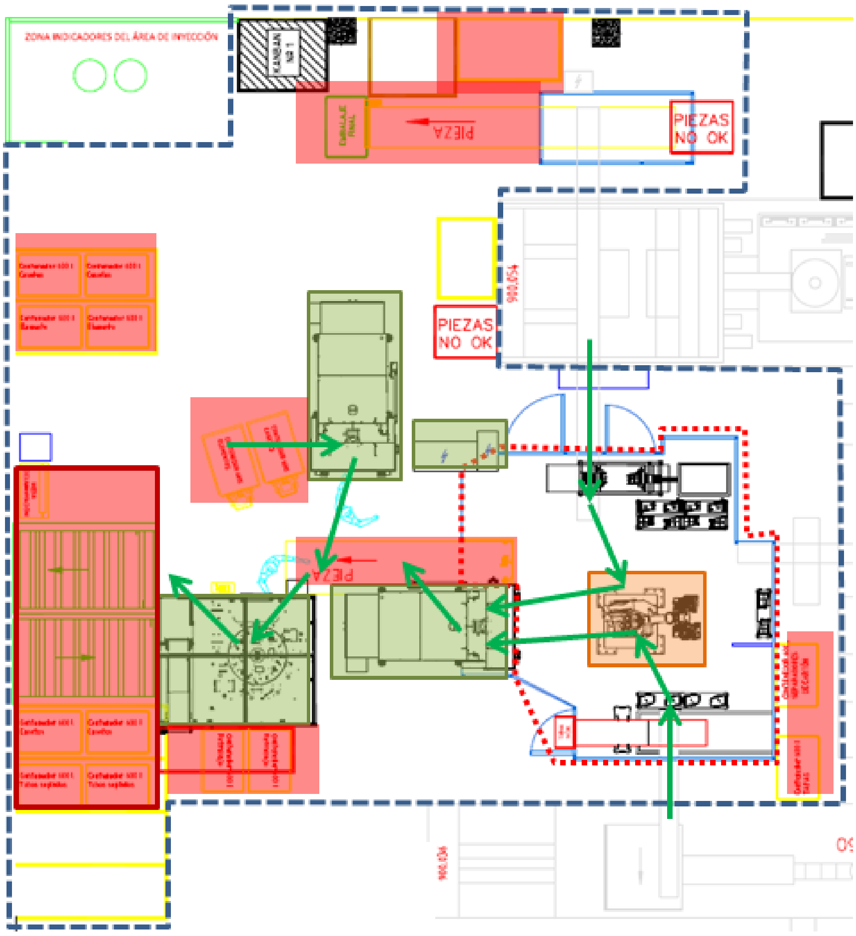


Figura 3.9. *Evolución del layout. Célula con robotización tradicional en el estado inicial.*

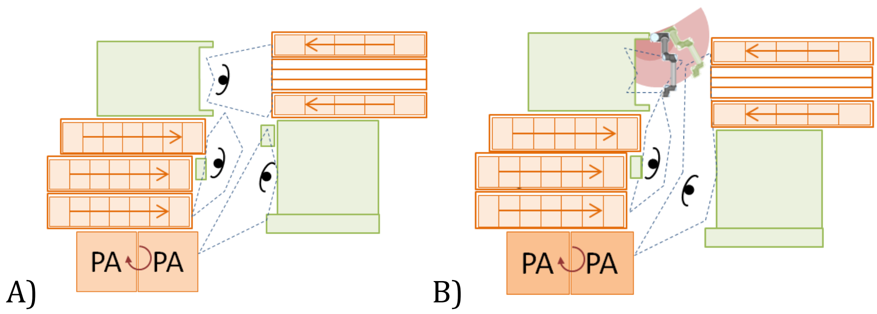


Figura 3.10. *Evolución del layout. A) Célula desautomatizada. B) Célula automatizada con Cobot.*

4. Conclusiones.

Esta tesis ha mostrado que los Sistemas de Producción Lean (inspirados en el Sistema de Producción Toyota) mantienen su plena vigencia como forma de organización para crear entornos industriales eficientes y compactos, especialmente ante la necesidad de producir en series cortas y variadas. También ha puesto de relieve que hay una brecha de conocimiento en una de las condiciones necesarias para su éxito: la integración de las personas en el sistema.

Esta tesis ha contribuido a crear conocimiento científico en el ámbito del Diseño de Sistemas de Producción Lean y, en particular, sobre cómo avanzar en mitigar la paradoja que plantea una puesta en marcha muy sesgada hacia el aumento de la productividad humana. A saber, cómo pretender involucrar a las personas en un proceso que puede deteriorar sus condiciones laborales y, en el límite, acarrear la pérdida del propio empleo. Las contribuciones de la tesis son en dos ámbitos:

- Proponiendo una metodología de diseño del Sistema Productivo (denominada *Person-Based Design,* Diseño desde la persona) que, basada en el concepto seminal *respect-for-human*, pone el respeto y la dignidad de las personas en el centro y origen del diseño. Sin renunciar por ello a elevados niveles de productividad, calidad y flexibilidad (Gil Vilda et al., 2019).
- Desarrollando las pautas de diseño de las primeras capas de la metodología *Person-Based Design* orientadas a la mejora de la productividad del espacio. Este enfoque es menos agresivo con las personas que la mejora de la productividad humana, mayoritariamente investigada en el entorno académico y utilizada en la industria (Gil Vilda et al., 2018, 2020; Gil-Vilda et al., 2017).

Respecto a la metodología de diseño propuesta, consiste en un diseño por capas concéntricas que, partiendo del respeto a la persona, se dirige hacia el exterior diseñando de la forma más eficiente posible las siguientes capas: embalajes, puesto de trabajo, configuración de la célula de producción, logística interna, almacén y logística desde los proveedores. Con una única regla de diseño, aportación original de esta tesis: "las decisiones de diseño tomadas para optimizar una capa nunca pueden perjudicar la optimización de las capas que contiene" (Gil Vilda et al., 2019).

Respecto al desarrollo de pautas de diseño y optimización basadas en el indicador de productividad de la superficie (definido como unidades conformes producidas por unidad de tiempo y por metro cuadrado ocupado: $u/h/m^2$), esta tesis desarrolla con este enfoque las primeras capas de la metodología *Person-Based Design* hasta el diseño de la logística interna. En este sentido hace aportaciones originales detalladas en los artículos independientes, que se pueden complementar una vez los artículos se analizan con una perspectiva de conjunto. Estas aportaciones conjuntas son las siguientes:

- Las células en U (U-SAL) son muy adecuadas para conseguir configuraciones compactas en superficie y además aseguran elevados niveles de productividad humana, especialmente cuando el proceso de ensamblaje presenta una elevada precedencia. Es decir, hay poca posibilidad de alterar el orden de las tareas unitarias de montaje.
- La configuración que mejor permite gestionar la superficie ocupada por una línea de producción es la forma de "=" y el aprovisionamiento de materiales a través de carriles FIFO perpendiculares a los dos lados del "=" (ver figuras 3.3B y 3.4).
- Con esta configuración se ha desarrollado un modelo matemático que relaciona los diferentes parámetros que influyen en la ocupación de espacio con dos conclusiones originales (aunque contraintuitivas) que tienen repercusión en la lógica de diseño y en la toma de decisiones en función de los costes de la superficie, la inversión y la mano de obra:
    - La superficie ocupada tiene una relación cuadrática respecto a la velocidad de producción de la línea. Esta conclusión refuerza la idoneidad de producir al ritmo más bajo posible. Es decir, al *Takt Time* del cliente evitando la sobreproducción, incluso considerando la posibilidad de construir varias células idénticas más lentas en lugar de una única célula más rápida. Esta última idea es especialmente relevante en células multi-producto porque además aumenta la

flexibilidad del sistema permitiendo producir el paralelo tantas referencias diferentes como células equivalentes haya.

- Una vez fijada la velocidad de la línea, puede controlarse la superficie ocupada a través del ciclo de aprovisionamiento de sus puestos de trabajo. Sobre la base de un aprovisionamiento cíclico (denominado *In-plant milk-run*), cuanto menor sea el ciclo de aprovisionamiento (aprovisionamientos más frecuentes) menor serán los materiales depositados en la línea y, por lo tanto, el espacio ocupado. El modelo propuesto permite calcular la reducción de la superficie como consecuencia de un aumento de la frecuencia de aprovisionamiento (con su correspondiente incremento de tiempo de transporte).

- La conclusión anterior lleva a la idea de relacionar el diseño de la célula en U con el diseño del *milk-run* que la suministra. Un ciclo de aprovisionamiento más corto implica menos superficie de la célula y menor longitud del tren (por tanto, menos recorridos del conductor máquina-vagones-máquina); a cambio implica un mayor tiempo de conducción almacén-célula-almacén. Este hecho sugiere la existencia de un óptimo para el ciclo de reaprovisionamiento que minimiza el trabajo humano. Esta tesis desarrolla una formulación matemática que permite definir la carga de trabajo en función del ciclo de aprovisionamiento y, en consecuencia, calcular su mínimo.

Finalmente, esta tesis muestra cómo las nuevas tecnologías desarrolladas bajo el paraguas de la Industria 4.0 (en particular la robótica colaborativa) pueden integrase en un Sistema de Producción Lean mejorando la productividad del espacio, mejorando la productividad humana y respetando a las personas (el cobot realiza operaciones de poco valor e incómodas para el ser humano) sin mermar la flexibilidad del sistema. Un ejemplo, por tanto, de la recientemente creada área de investigación denominada *Lean 4.0*.

5. Trabajo futuro.

Cada uno de los artículos presentados propone en sus conclusiones vías de continuidad concretas de trabajo futuro para los temas desarrollados.

Adicionalmente, y con una vista de conjunto, esta tesis abre líneas de trabajo que pueden orientarse en el futuro hacia varios ámbitos.

5.1. Desarrollo de la metodología de diseño "*Person-Based Design*".

La metodología propuesta puede continuar desarrollándose con las siguientes líneas de trabajo:

- Profundizar en el detalle de los modelos propuestos para las capas 1 a 5 para reducir las simplificaciones y hacerlos más precisos. Bien a través de modelización matemática, bien a través de simulación discreta.
- Desarrollar modelos de las capas exteriores para diseñar almacenes adaptados al *picking* intensivo (requeridos por el suministro *milk-run*) que garanticen la compactación del espacio y la ergonomía de las manipulaciones frecuentes.
- Combinar los modelos propuestos para las Células en U y los Circuitos de Suministro *milk-run* (más las capas exteriores a desarrollar) para crear un modelo geométrico de fábrica manufacturera optimizada en superficie.
- Utilizar la simulación discreta para contrastar los modelos definidos.
- Aplicar el método de diseño sobre el terreno en entornos reales y comparar sus resultados respecto a otras metodologías de diseño.

5.2. Desarrollar el concepto Lean 4.0.

Desarrollar el concepto Lean 4.0 como un Sistemas de Producción Lean clásico que incorpora las tecnologías de la Industria 4.0 para seguir eliminando derroches de los procesos y aumentando la flexibilidad.

Dos áreas de trabajo futuro son posibles:

- La identificación y validación de tecnologías que puedan ser integradas en un Sistema de Producción Lean para reducir realmente el derroche sin comprometer la flexibilidad del sistema o aumentar innecesariamente la complejidad.
- Investigar los nuevos requerimientos que estas tecnologías introducen en el principio Lean *respect-for-human* como pilar necesario para la sostenibilidad del sistema.

5.3. Incorporar nuevas disciplinas científicas más allá de la ingeniería en el diseño y gestión de los Sistemas de Producción Lean.

El actual estudio de los Sistemas de Producción Lean se realiza prácticamente en exclusiva desde disciplinas de Ingeniería.

Una visión como sistema socio-técnico abre la puerta a un enfoque mucho más multidisciplinar que el actual que permita incorporar otras disciplinas científicas. A lo largo del desarrollo de esta tesis se han intuido las siguientes:

- Psicología. Todo el estudio de la parte humana del sistema se puede estudiar desde el campo de la psicología desde diversas ópticas: motivación, cognición, aprendizaje, etc. que con seguridad aportarían enfoques nuevos para mitigar las resistencias al cambio y conseguir un mayor bienestar físico y mental de las personas en sus puestos de trabajo.
- Sociología. Una organización (incluida una fábrica) no deja de ser una micro sociedad en la que pueden investigarse las interacciones entre grupos y colectivos.
- Antropología. En las organizaciones (incluidas las fábricas) como micro sociedades que son, no es difícil identificar mitos fundacionales, grupos en competencia, personas de referencia, incluso líneas de pensamiento con rasgos espirituales. Estudiar estos fenómenos con un enfoque antropológico podría explicar (y hacer más predecible) el comportamiento humano en estos contextos y facilitar los procesos de cambio organizacional.

5.4. Del "Lean Manufacturing System" al "Lean-Compact Manufacturing System".

Como propuesta final la idea creativa de desarrollar los campos de trabajo futuro propuestos en esta tesis bajo una denominación original:

"Lean-Compact Manufacturing System"

Uno de los hilos conductores de esta tesis es, con el objetivo de reducir la presión sobre las personas, focalizar la medición de eficiencia de un Sistema de Producción Lean en la productividad de la superficie (unidades/hora/m2) frente a la tradicional productividad humana (unidades/hora/persona).

"Lean-Compact Manufacturing System" sería una adaptación de los Sistemas de Producción Lean focalizado en la sistemática reducción de la superficie industrial como único indicador para la mejora.

La hipótesis es prometedora dado la compactación de la superficie aumenta la eficiencia del sistema a través de dos mecanismos:

- La reducción de superficie disminuye derroches: transportes, movimientos, esperas.
- Para reducir la superficie es necesario reducir derroches que acaban ocupando superficie: sobreproducción, stock, sobre procesamiento, rechazos y retrabajos.

Como reflexión final, el área de investigación sobre Sistemas de Producción Lean en el entorno industrial tiene plena vigencia después de 70 años de historia, tanto profundizando en líneas de trabajo ya propuestas como abriendo nuevas vías más innovadoras. Los Sistemas de Producción Lean pueden seguir contribuyendo a crear entornos industriales más ágiles, más productivos y más compactos, asegurando el respeto por las personas que lo integran.

6. Apéndices

6.1. Factor de Impacto de las publicaciones

Procedia Manufacturing 2017. El factor de impacto SJR para Procedia Manufacturing en el año 2017 fue 0,201. Estuvo en el 3r cuartil en la categoría "Industrial and Manufacturing Engineering”.

CIRP Annals 2018. El factor de impacto JCR para CIRP Annals en 2018 fue 3,826. Estuvo en la posición 10 de 49 (1r cuartil) en la categoría “Engineering, Manufacturing”.

Procedia Manufacturing 2019. El factor de impacto SJR para Procedia Manufacturing en el año 2019 fue 0,516. Estuvo en el 2ª cuartil en la categoría "Industrial and Manufacturing Engineering”.

CIRP Annals 2020. El factor de impacto JCR para CIRP Annals en 2020 fue 3,916. Estuvo en la posición 19 de 50 (2º cuartil) en la categoría “Engineering, Manufacturing”.

Applied Sciences 2021. El factor de impacto JCR para Applied Sciences en 2020 (último valor publicado) fue 2,679. Estuvo en la posición 38 de 90 (2º cuartil) en la categoría “Engineering, Multidisciplinary”.

6.2. Justificación de la coautoría

Esta subsección resume las principales contribuciones del autor en cada una de las publicaciones de esta tesis por compendio:

Gil-Vilda, F., Sune, A., Yagüe-Fabra, J. A., Crespo, C., & Serrano, H. (2017). Integration of a collaborative robot in a U-shaped production line: a real case study. *Procedia Manufacturing, 13.*

- Estado del arte.
- Recopilación de los datos reales sobre el terreno.
- Análisis comparativo y conclusiones.
- Redacción del texto.

Gil Vilda, F., Yagüe-Fabra, J. A., Sune Torrents, A., Jauregui-Becker, J. M., & Wits, W. W. (2018). A geometrical model for managing surface productivity of U-shaped assembly lines. *CIRP Annals, 67(1).*

- Estado del arte.
- Aportación de 4 casos de estudio.
- Desarrollo del modelo matemático.
- Redacción del manuscrito.

Gil Vilda, F., Yagüe Fabra, J. A., & Sunyer Torrents, A. (2019). Person-based design: A human-centered approach for lean factory design. *Procedia Manufacturing, 41.*

- Estado del arte.
- Propuesta modelo simplificado Sistema de Producción.
- Definición método de diseños "*Person-Based Design*" (Diseño desde la persona).
- Desarrollo del caso de estudio.
- Redacción del manuscrito.

Gil Vilda, F., Yagüe-Fabra, J. A., & Sunyer Torrents, A. (2020). An in-plant milk-run design method for improving surface occupation and optimizing mizusumashi work time. *CIRP Annals, 69(1).*

- Estado del arte.
- Identificación de los parámetros relevantes para la modelización.
- Desarrollo del modelo matemático.
- Redacción del manuscrito.

Gil-Vilda, F., Yagüe-Fabra, J. A., & Sunyer, A. (2021). From lean production to lean 4.0: A systematic literature review with a historical perspective. *Applied Sciences (Switzerland) (Vol. 11, Issue 21).*

- Estado del arte.
- Definición de la SLR (Revisión Sistemática de la Literatura).
- Recopilación de los datos de WoS y Scopus.
- Análisis y síntesis de los registros. Definición de criterios de agrupamiento.
- Redacción del manuscrito.

7. Bibliografía

Se presenta a continuación la bibliografía referenciada en esta memoria que debe complementarse con la bibliografía referenciada en cada artículo.

Aase, G. R., Olson, J. R., & Schniederjans, M. J. (2004). U-shaped assembly line layouts and their impact on labor productivity: An experimental study. *European Journal of Operational Research*, *156*(3). https://doi.org/10.1016/S0377-2217(03)00148-6

Alves, A. C., Ferreira, A. C., Maia, L. C., Leão, C. P., & Carneiro, P. (2019). A symbiotic relationship between Lean Production and Ergonomics: Insights from Industrial Engineering final year projects. *International Journal of Industrial Engineering and Management*, *10*(4). https://doi.org/10.24867/IJIEM-2019-4-244

Antony, J., Psomas, E., Garza-Reyes, J. A., & Hines, P. (2020). Practical implications and future research agenda of lean manufacturing: a systematic literature review. *Production Planning and Control*. https://doi.org/10.1080/09537287.2020.1776410

Arezes, P. M., Dinis-Carvalho, J., & Alves, A. C. (2015). Workplace ergonomics in lean production environments: A literature review. In *Work* (Vol. 52, Issue 1). https://doi.org/10.3233/WOR-141941

Bhamu, J., & Sangwan, K. S. (2014). Lean manufacturing: Literature review and research issues. In *International Journal of Operations and Production Management* (Vol. 34, Issue 7, pp. 876–940). Emerald Group Publishing Ltd. https://doi.org/10.1108/IJOPM-08-2012-0315

Bidanda, B., Ariyawongrat, P., Needy, K. L., Norman, B. A., & Tharmmaphornphilas, W. (2005). Human related issues in manufacturing cell design, implementation, and operation: A review and survey. *Computers and Industrial Engineering*, *48*(3). https://doi.org/10.1016/j.cie.2003.03.002

Blank, S. (2013). Why the lean start-up changes everything. In *Harvard Business Review* (Vol. 91, Issue 5).

Botti, L., Mora, C., Piana, F., & Regattieri, A. (2018). The impact of ergonomics on the design of hybrid multi-model production lines in lean manufacturing. *Advances in Intelligent Systems and Computing*, *606*. https://doi.org/10.1007/978-3-319-60474-9_16

Bounine, J., & Suzaki, K. (1986). *Produire Juste a temps. Les sources de la productivité japonaise.* Masson.

Bowen, D. E., & Youngdahl, W. E. (1998). "Lean" service: In defense of a production-line approach. *International Journal of Service Industry Management*, *9*(3). https://doi.org/10.1108/09564239810223510

Brito, M. F., Ramos, A. L., Carneiro, P., & Gonçalves, M. A. (2020). A continuous improvement assessment tool, considering lean, safety and ergonomics. *International Journal of Lean Six Sigma*, *11*(5). https://doi.org/10.1108/IJLSS-12-2017-0144

Ciano, M. P., Pozzi, R., Rossi, T., & Strozzi, F. (2019). How IJPR has addressed 'lean': a literature review using bibliometric tools. In *International Journal of Production Research* (Vol. 57, Issues 15–16, pp. 5284–5317). Taylor and Francis Ltd. https://doi.org/10.1080/00207543.2019.1566667

Coffey, D., & Thornley, C. (2006). Automation, motivation and lean production reconsidered. *Assembly Automation*, *26*(2). https://doi.org/10.1108/01445150610658068

Conti, R., Angelis, J., Cooper, C., Faragher, B., & Gill, C. (2006). The effects of lean production on worker job stress. *International Journal of Operations and Production Management*, *26*(9). https://doi.org/10.1108/01443570610682616

Cusumano, M. A. (1985). *The Japanese Automobile Industry: Technology and Management at Nissan and Toyota*. Council on East Asian Studies, Harvard

University and distributed by the Harvard University Press. https://books.google.es/books?id=cc2N4fCsVaAC

da Silva, M. P., Tortorella, G. L., & Amaral, F. G. (2016). Psychophysical Demands and Perceived Workload—An Ergonomics Standpoint for Lean Production in Assembly Cells. *Human Factors and Ergonomics In Manufacturing*, *26*(6). https://doi.org/10.1002/hfm.20404

Danese, P., Manfè, V., & Romano, P. (2018). A Systematic Literature Review on Recent Lean Research: State-of-the-art and Future Directions. *International Journal of Management Reviews*, *20*(2), 579–605. https://doi.org/10.1111/ijmr.12156

Denyer, D., & Tranfield, D. (2009). Producing a Systematic Review. In *The SAGE Handbook of Organizational Research Methods*.

Dorval, M., Jobin, M. H., & Benomar, N. (2019). Lean culture: a comprehensive systematic literature review. In *International Journal of Productivity and Performance Management* (Vol. 68, Issue 5, pp. 920–937). Emerald Group Holdings Ltd. https://doi.org/10.1108/IJPPM-03-2018-0087

Florida, R. (1996). Lean and green: The move to environmentally conscious manufacturing. *California Management Review*, *1*. https://doi.org/10.2307/41165877

Furterer, S., & Elshennawy, A. K. (2005). Implementation of TQM and Lean Six Sigma tools in local government: A framework and a case study. *Total Quality Management and Business Excellence*, *16*(10). https://doi.org/10.1080/14783360500236379

Fynes, B., & Ennis, S. (1994). From lean production to lean logistics: The case of microsoft Ireland. *European Management Journal*, *12*(3). https://doi.org/10.1016/0263-2373(94)90067-1

Gil Vilda, F., Yagüe Fabra, J. A., & Sunyer Torrents, A. (2019). Person-based design: A human-centered approach for lean factory design. *Procedia Manufacturing*, *41*. https://doi.org/10.1016/j.promfg.2019.09.031

Gil Vilda, F., Yagüe-Fabra, J. A., Sune Torrents, A., Jauregui-Becker, J. M., & Wits, W. W. (2018). A geometrical model for managing surface productivity of U-shaped assembly lines. *CIRP Annals*, *67*(1). https://doi.org/10.1016/j.cirp.2018.04.047

Gil Vilda, F., Yagüe-Fabra, J. A., & Sunyer Torrents, A. (2020). An in-plant milk-run design method for improving surface occupation and optimizing mizusumashi work time. *CIRP Annals*, *69*(1). https://doi.org/10.1016/j.cirp.2020.03.012

Gil-Vilda, F., Sune, A., Yagüe-Fabra, J. A., Crespo, C., & Serrano, H. (2017). Integration of a collaborative robot in a U-shaped production line: a real case study. *Procedia Manufacturing*, *13*. https://doi.org/10.1016/j.promfg.2017.09.015

Gil-Vilda, F., Yagüe-Fabra, J. A., & Sunyer, A. (2021). From lean production to lean 4.0: A systematic literature review with a historical perspective. In *Applied Sciences (Switzerland)* (Vol. 11, Issue 21). https://doi.org/10.3390/app112110318

Giroux, H. (2006). "It was such a handy term": Management fashions and pragmatic ambiguity. *Journal of Management Studies*, *43*(6). https://doi.org/10.1111/j.1467-6486.2006.00623.x

Gorlach, I., & Wessel, O. (2008). Automation or de-automation. *AIP Conference Proceedings*, *1045*. https://doi.org/10.1063/1.2991345

Graban, M. (2009). Lean hospitals: Improving quality, patient safety, and employee engagement. In *Lean Hospitals: Improving Quality, Patient Safety, and Employee Engagement, Third Edition*.

Hall. (1983). *Zero Inventory*. Dow Jones-Irwin.

Hall. (1987). *Attaining Manufacturing Excellence: Just-in-time, Total Quality, Total People Involvement*. Dow Jones-Irwin. https://books.google.es/books?id=LXanXMIh-ncC

Hasle, P., Bojesen, A., Jensen, P. L., & Bramming, P. (2012). Lean and the working environment: A review of the literature. In *International Journal of Operations and Production Management* (Vol. 32, Issue 7, pp. 829–849). https://doi.org/10.1108/01443571211250103

Hines, P., Holwe, M., & Rich, N. (2004). Learning to evolve: A review of contemporary lean thinking. In *International Journal of Operations and Production Management* (Vol. 24, Issue 10, pp. 994–1011). https://doi.org/10.1108/01443570410558049

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management*, *25*(2), 420–437. https://doi.org/10.1016/j.jom.2006.04.001

Jasti, N. V. K., & Kodali, R. (2014). A literature review of empirical research methodology in lean manufacturing. In *International Journal of Operations and Production Management* (Vol. 34, Issue 8, pp. 1080–1122). Emerald Group Publishing Ltd. https://doi.org/10.1108/IJOPM-04-2012-0169

Jasti, N. V. K., & Kodali, R. (2015). Lean production: Literature review and trends. *International Journal of Production Research*, *53*(3), 867–885. https://doi.org/10.1080/00207543.2014.937508

Karlsson, C., & Åhlström, P. (1996). The difficult path to lean product development. *Journal of Product Innovation Management*, *13*(4). https://doi.org/10.1016/S0737-6782(96)00033-1

Koskela, L. (1994). Lean production in lean construction. *National Construction and Management Conference*.

Krafcik, J. F. (1988). Triumph Of The Lean Production System. *Sloan Management Review*, *30*(1).

Lamming, R. (1996). Squaring lean supply with supply chain management. In *International Journal of Operations and Production Management* (Vol. 16, Issue 2). https://doi.org/10.1108/01443579610109910

Lewchuk, W., & Robertson, D. (1996). Working conditions under lean production: A worker-based benchmarking study. *Asia Pacific Business Review*, *2*(4). https://doi.org/10.1080/13602389600000020

Liker, J. (2004). The Toyota Way - 14 management principles the world's greatest manufacturer. In *McGraw-Hill* (Vol. 11).

Liker, J., & Meier, D. (2007). Toyota Talent, Developing your people the Toyota Way. In *American Media International*.

Locher, D. (2011). *Lean Office and Service Simplified: The Definitive How-To Guide*. Taylor & Francis.

Magnani, F., Carbone, V., & Moatti, V. (2019). The human dimension of lean: a literature review. *Supply Chain Forum*, *20*(2), 132–144. https://doi.org/10.1080/16258312.2019.1570653

Marodin, G. A., & Saurin, T. A. (2013). Implementing lean production systems: Research areas and opportunities for future studies. *International Journal of Production Research*, *51*(22). https://doi.org/10.1080/00207543.2013.826831

Metternich, J., Müller, M., Meudt, T., & Schaede, C. (2017). Lean 4.0 - Between contradiction and vision. *Lean 4.0 - Between Contradiction and Vision*, *112*(5). https://doi.org/10.3139/104.111717

Miltenburg, J. (2001). U-shaped production lines: A review of theory and practice. *International Journal of Production Economics*, *70*(3). https://doi.org/10.1016/S0925-5273(00)00064-5

Monden, Y. (1983). Toyota production system: Practical approach to production management. In *Atlanta, G.A.*

Moyano-Fuentes, J., & Sacristán-Díaz, M. (2012). Learning on lean: A review of thinking and research. In *International Journal of Operations and Production Management* (Vol. 32, Issue 5, pp. 551–582). https://doi.org/10.1108/01443571211226498

Muramatsu, R., Miyazaki, H., & Ishii, K. (1987). A successful Application of Job Enlargement/Ennchment at Toyota. *IIE Transactions (Institute of Industrial Engineers)*, *19*(4). https://doi.org/10.1080/07408178708975419

New, S. J. (2007). Celebrating the enigma: The continuing puzzle of the Toyota Production System. In *International Journal of Production Research* (Vol. 45, Issue 16). https://doi.org/10.1080/00207540701223386

Ó hUallacháin, B., & Wasserman, D. (1999). Vertical integration in a lean supply chain: Brazilian automobile component parts. *Economic Geography*, *75*(1). https://doi.org/10.1111/j.1944-8287.1999.tb00072.x

Ohno, T. (1978). *Toyota seisan hoshiki: Datsukibo no keiei wo mezashi*. Daiyamondo sha.

Ohno, T. (1982). How the Toyota Production System was Created. *Japanese Economic Studies*, *10*(4). https://doi.org/10.2753/jes1097-203x100483

Oliver, N., & Davies, A. (1990). ADOPTING JAPANESE-STYLE MANUFACTURING METHODS: A TALE OF TWO (UK) FACTORIES*. *Journal of Management Studies*, *27*(5). https://doi.org/10.1111/j.1467-6486.1990.tb00261.x

Petrovic, O., & Zsifkovits, H. E. (1994). Business process re-engineering as an enabling factor for lean management. In *IFIP Transactions A: Computer Science and Technology* (Issue A-54).

Portioli-Staudacher, A. (2008). Lean healthcare. An experience in Italy. *IFIP International Federation for Information Processing*, *257*. https://doi.org/10.1007/978-0-387-77249-3_50

Powell, C. (1993). Lean manufacturing organization, 21st century. *Annual International Conference Proceedings - American Production and Inventory Control Society*.

Psomas, E., & Antony, J. (2019). Research gaps in Lean manufacturing: a systematic literature review. In *International Journal of Quality and Reliability Management*

(Vol. 36, Issue 5, pp. 815–839). Emerald Group Holdings Ltd. https://doi.org/10.1108/IJQRM-12-2017-0260

Pujawan, I. N., & Bah, A. U. (2022). Supply chains under COVID-19 disruptions: literature review and research agenda. In *Supply Chain Forum* (Vol. 23, Issue 1). https://doi.org/10.1080/16258312.2021.1932568

Rehder, R. R. (1992). Building Cars As if People Mattered. The Japanese Lean System vs Volvo's Uddevalla System. *The Colubmia Journal of World Business*.

Rother, M. (2009). Toyota Kata. In *Journal of Chemical Information and Modeling*.

Sato K., & Hoshino Y. (1984). *The anatomy of Japanase Business*. M.E. Sharpe.

Schonberger, R. J. (1982). *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*. The Free Press.

Schonberger, R. J. (2019). The disintegration of lean manufacturing and lean management. *Business Horizons*, *62*(3). https://doi.org/10.1016/j.bushor.2019.01.004

Shah, R., & Ward, P. T. (2007). Defining and developing measures of lean production. *Journal of Operations Management*, *25*(4), 785–805. https://doi.org/10.1016/j.jom.2007.01.019

Shimada, H., & MacDuffie, J. P. (1986). *Industrial relations and 'humanware'* (Cambridge, MA).

Shingo, S. (1898). *A Study of the Toyota Production System: From an Industrial Engineering Viewpoint (Produce What Is Needed, When It's Needed)*. Productitivity Press.

Shingo, S. (1981). *Study of "TOYOTA", Production System from Industrial Engineering Viewpoint*. Japan Management Association.

Shingō, S. (1985). *A Revolution in Manufacturing: The SMED System*. Productivity Press.

Skorstad, E. (1994). Lean Production, Conditions of Work and Worker Commitment. *Economic and Industrial Democracy*, *15*(3). https://doi.org/10.1177/0143831X94153005

Sugimori, Y., Kusunoki, K., Cho, F., & Uchikawa, S. (1977). Toyota production system and kanban system materialization of just-in-time and respect-for-human system. *International Journal of Production Research*, *15*(6), 553–564. https://doi.org/10.1080/00207547708943149

Taiichi Ohno. (1988). *Toyota Production System: Beyond Large-Scale Production*. Productivity Press.

Taylor, L. T. (1994). Quality initiatives: Are they changing business practices worldwide? In *IFIP Transactions A: Computer Science and Technology* (Issue A-52).

Tortorella, G. L., Vergara, L. G. L., & Ferreira, E. P. (2017). Lean manufacturing implementation: an assessment method with regards to socio-technical and ergonomics practices adoption. *International Journal of Advanced Manufacturing Technology*, *89*(9–12). https://doi.org/10.1007/s00170-016-9227-7

Wang, Z., & Sun, Z. (2021). From Globalization to Regionalization: The United States, China, and the Post-Covid-19 World Economic Order. *Journal of Chinese Political Science*, *26*(1). https://doi.org/10.1007/s11366-020-09706-3

Williams, K., Haslam, C., Williams, J., Cutler, T., Adcroft, A., & Sukhdevjohal, S. (1992). Against Lean Production. *Economy and Society*, *21*(3). https://doi.org/10.1080/03085149200000016

Womack, J. P., & Jones, D. T. (1996a). From lean production to the lean enterprise. *IEEE Engineering Management Review*, *24*(4).

Womack, J. P., & Jones, D. T. (1996b). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Simon & Schuster.

Womack, J. P., Jones, D. T., & Roos, D. (1990). The machine that changed the world, Rawson Associates. *New York*.

Yusoff, S. M., Arezes, P., & Costa, N. (2013). The Integration of Lean Manufacturing and Ergonomics Approach in Workplace Design. *Occupational Safety and Hygiene - Sho2013*.

En las cuatro últimas décadas, el incremento de la competitividad de los mercados globales ha popularizado en término “lean” como una forma de organización industrial capaz de conseguir altos niveles de calidad, productividad y cortos plazos de entrega, en un entorno de producción de series cortas y variadas. Tanto es así que su sobreuso ha generado confusión y una cierta pérdida de su sentido original.

Los Sistemas de Producción Lean se basan en el Sistema de Producción Toyota, desarrollado en los años 60 del siglo XX y ampliamente difundido a partir de los años 90 como “*Lean Production*” tras las conclusiones del IMVP conducido por el MIT desde 1979.

Uno de los pilares fundacionales del Sistema es el respeto por las personas (*respect-for-human*). Sin embargo, la bibliografía muestra una falta de interés paradójica sobre este concepto, a la vez que una progresiva pérdida de visión holística en favor de las herramientas.

En este sentido, hay documentada en la bibliografía una paradoja difícil de conciliar: ¿cómo implicar a las personas en la mejora de la eficiencia del sistema si ello puede acarrear su despido?

El objeto de esta tesis es proponer una metodología de diseño para Sistemas de Producción Lean que ayude a mitigar esta paradoja y se apoye, como indicador de mejora, en la productividad de la superficie en lugar de la tradicional productividad humana.

Para ello propone el método *Person-Based Design* (Diseño desde la Persona) en siete capas concéntricas con una única regla de diseño: mejorar la eficiencia de cada capa sin que con ello se perjudique la eficiencia de las capas que contiene.

Después desarrolla metodologías concretas de diseño y optimización de las cinco primeras capas basadas en la reducción del espacio industrial. En particular, modeliza una topología de Células en U orientada a la gestión optima del espacio ocupado. Después, propone un método de diseño de su sistema de aprovisionamiento (*milk-run*) para minimizar superficie y esfuerzo del conductor. Finalmente, muestra cómo Lean 4.0, con la introducción de tecnologías de la Industria 4.0, puede contribuir a compactar células de producción eliminado trabajos penosos para las personas a través del uso de Cobots.