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UM ESTUDO DAS RELAÇÕES ENTRE A PRODUÇÃO ENXUTA E A INDÚSTRIA 4.0 E POSSÍVEIS CAMINHOS PARA A TRANSFORMAÇÃO DIGITAL EM HEALTHCARE

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LISTA DE ABREVIAÇÕES

LP	Lean Production
STP	Sistema Toyota de Produção
I4.0	Indústria 4.0
LF	Learning Factory

SUMÁRIO

Resumo

Os sistemas de produção enxutos têm mostrado resultados positivos na redução de desperdícios e agregação de valor em várias organizações. Além disso, novas tecnologias relacionadas à Indústria 4.0 surgiram nos últimos anos, como Sistemas Ciberfísicos, Internet das Coisas, Big Data, entre outros. O avanço destes conceitos encorajou a investigação da relação entre ambos os conceitos, de modo a identificar os resultados da união entre produção enxuta e tecnologias da indústria 4.0. A presente pesquisa procura apontar as relações e a falta de compreensão sobre vários aspectos entre a união desses conceitos, apresentando lacunas de pesquisa, especialmente na cadeia de suprimentos de saúde. Para tanto, foram realizados dois mapeamentos científicos utilizando software bibliométricos como SciMAT e VOSviewer. Os resultados apresentam a falta de compreensão frente a diversos desafios relacionados às tecnologias emergentes, bem com a relação de tais tecnologias com as técnicas de produção enxuta, principalmente em sistemas de saúde. Por fim, uma proposta de *survey* foi desenvolvido a fim de compreender as relações entre ambos os conceitos na performance operacional em sistemas de saúde.

Palavras-chave: Mapeamento científico, Produção Enxuta, Indústria 4.0, Quarta Revolução Industrial, Saúde.

1 Introdução

No futuro, o sucesso de uma organização dependerá de como ela lida com os desafios da sustentabilidade (SHET, SETHIS e SRINIVAS, 2011). Além disso, o alto grau de competitividade do mercado atual exige que as organizações sejam assertivas em atender às reais necessidades dos clientes, bem como um compromisso constante com a qualidade do produto e a disposição de resíduos (KUMAR, 2018). Entre as muitas filosofias de gerenciamento existentes que orientam as organizações a se tornarem mais competitivas e sustentáveis, o Lean Production (LP) ou o Sistema Toyota de Produção (STP) tem sido amplamente utilizado pelas organizações, pois promove baixos custos de produção e alcança resultados. desde a eliminação de resíduos de todas as áreas da organização, aumentando a produtividade e a lucratividade, com foco no cliente (OLIVEIRA, SÁ E FERNANDES 2017; BAUER, 2018). Por outro lado, a quarta revolução industrial, também conhecida como Indústria 4.0 (I4.0), está transformando organizações em fábricas inteligentes através do uso de informações analíticas avançadas, bem como da comunicação e colaboração entre pessoas e máquinas (LEE; BAGHERI; KAO 2015). Schumacher, Erol e Sihn (2016) I4.0 apontam avanços tecnológicos nos quais a Internet e outras tecnologias integrarão objetos físicos, ação humana, máquinas inteligentes, linhas de produção e processos organizacionais para formar uma cadeia de valor inteligente. Essa revolução industrial apresenta uma excelente oportunidade para a construção de organizações sustentáveis, baseadas na harmonia entre os três pilares da sustentabilidade: social, econômico e ambiental (STOCK e SELIGER, 2016).

1.1 Tema e problema

Devido ao aumento da demanda do consumidor, novas tecnologias precisam ser exploradas para reforçar as ferramentas de LP. Sabe-se que o LP não utiliza todo o potencial das tecnologias da informação, o que a torna uma filosofia limitada, de modo que as lacunas nos conceitos de LP possam ser preenchidas usando as tecnologias I4.0 (KOLBERG, KNOBLOCH e ZÜHLKE, 2017; TORTORELLA e FETTERMANN, 2018). A I4.0 visa aumentar a produtividade e a flexibilidade das organizações. Tais características são evidenciadas nos princípios do LP que, embora esses conceitos apresentem abordagens diferentes, tenham objetivos comuns (FRANK, 2014; BUER, STRANDHAGEN e CHAN, 2018). A união entre esses conceitos tem suporte mútuo, em que os métodos de LP facilitam a implementação da I4.0 e, da mesma forma, a I4.0 aprimora os conceitos de LP.

Estudos sobre a relação entre LP e I4.0 estão ganhando importância no mundo científico. Os pesquisadores estão se esforçando para entender como a unidade de conceitos se inter-relaciona na prática. A revisão sistemática da literatura de BUER, STRANDHAGEN e CHAN, 2018) indica tais relações, mostrando resultados positivos e propondo uma estrutura inicial para essa integração. No entanto, faltam estudos sobre as implicações no desempenho organizacional e os fatores ambientais que influenciam essas relações. Wagner, Herrmann e Thiede (2017) demonstraram por meio de uma matriz o grau de impacto das tecnologias I4.0 nos sistemas de produção existentes que usam os princípios de LP, propondo formas de integrar conceitos focados no princípio Just-in-Time e, como sugestões para trabalho futuro, proponha a relação dessas filosofias com a sustentabilidade. Kadri (2010), Aurelio et al. (2011); Jadhav, Mantha e Rane (2014) apontam que poucas organizações que não são japonesas foram bem-sucedidas na aplicação de LP devido aos vários desafios e barreiras encontrados durante seu processo de implementação. Sanders, Elangeswaran e Wulfsberg (2016) destacam várias abordagens e tecnologias fornecidas pela I4.0 para superar essas limitações, mas estudos práticos desses conceitos correlatos estão ausentes na literatura.

As tecnologias LP e I4.0 também podem ser usadas para melhorar o desempenho operacional da cadeia de suprimentos da área de saúde, bem como a satisfação do paciente (ILANGAKOON, WEERABAHU e WICKRAMARACHCHI, 2018). No entanto, Poksinska (2010) aponta que apenas a implantação de novas tecnologias pelo neste setor não será suficiente. Portanto, a implementação de técnicas enxutas nos processos operacionais na saúde maximizará ainda mais o desempenho operacional, eliminando o desperdício e as atividades que não agregam valor. Ghosh, Dohan e Veldandi (2018) apontam que, devido à falta de colaboração entre acadêmicos e profissionais de saúde, ainda existem lacunas na literatura para entender os principais fatores estratégicos da transformação digital na cadeia de valor deste setor. Assim, o problema desta pesquisa é: *a união das tecnologias I4.0 e das práticas Lean é um fator chave para a transformação digital da cadeia de suprimentos de saúde?*

1.2 Objetivos

1.2.1 Objetivo geral

- Identificar a relação entre a I4.0 com a PE e possíveis caminhos de pesquisa e aplicação em saúde.

1.2.2 Objetivos específicos

- Realizar uma análise bibliométrica sobre a I4.0, a fim de mapear o campo de pesquisa e compreender as relações com a PE.
- Identificar através de uma análise bibliométrica os temas estratégicos e a estrutura da evolução científica da produção enxuta e relações com a indústria 4.0.
- Estruturar uma proposta de *survey* para compreender os impactos das relações entre Indústria 4.0 e produção enxuta na performance operacional de sistemas de saúde.

1.3 Justificativa

1.3.1 Justificativa ambiental

No Relatório Bruntland, em 1987, o conceito de desenvolvimento sustentável foi definido como um desenvolvimento "capaz de atender às necessidades da geração atual sem comprometer a capacidade de atender às necessidades das gerações futuras" (STOCK, 2018). No entanto, o mundo está sofrendo drasticamente com os atuais meios de produção, que por sua vez geram problemas como o aquecimento global e o efeito estufa (SUN e LI, 2013); aumento do consumo global de energia (LAZAROIU e ROSCIA, 2012); crises agrícolas (ORT et al., 2015); redução do suprimento global de água (ADDAMS et al., 2009; WEBB, GEORGE e SHAHIN, 2018) etc. Além disso, estima-se que até 50% da produção de alimentos seja perdida ou descartada durante o processo de produção (HALL et al. 2009; DU et al., 2018), enquanto a demanda por carne deve aumentar em cerca de 85% até 2030 (BEDDINGTON, 2010). A população mundial aumentará de 7 para 9-11 bilhões em 2050 (SIEMIENIUCH et al., 2015). Esses dados demonstram alguns dos desafios e questões que precisam de atenção para promover uma produção mais eficiente, inteligente e sustentável.

1.3.2 Justificativa Social

A quarta revolução industrial impactará drasticamente as carreiras dos trabalhadores (HIRSCHI, 2018). Atividades manuais e trabalhos que não exigem alta qualificação deixarão de existir devido à automação de processos (HIRSCH-KREINSEN, 2016). Portanto, a formação dos trabalhadores precisa se adaptar, começando com um novo modelo de ensino e aprendizagem que se concentre no desenvolvimento de habilidades interdisciplinares e na capacidade dos jovens de resolver problemas, enfrentando os desafios apresentados em I4.0. Essa revolução tem consequências perturbadoras nas áreas social e econômica (Hirsch-Kreinsen, 2016). Para Benešová e Tupa (2017), a transição para uma produção tão sofisticada não será possível imediatamente devido aos altos custos financeiros, bem como à falta de funcionários qualificados capazes de lidar com essas tecnologias. Assim, o I4.0 traz desafios na esfera social, exigindo que as organizações desenvolvam sua força de trabalho nos mais altos níveis de habilidade e atraiam novos talentos capazes de lidar com a crescente complexidade inerente às novas tecnologias (WITTENBERG, 2016, ENKE et al., 2018) Além disso, é necessário o envolvimento dos funcionários para estimular habilidades como criatividade e planejamento de processos, pois elas serão a chave para implementar e assimilar inovações tecnológicas que transformarão dramaticamente o ambiente de trabalho (KAGERMANN et al., 2013). No entanto, Bauer (2018) destaca que, para que essas mudanças ocorram, é necessário um bom relacionamento entre as organizações e os colaboradores, que será fortalecido por meio de treinamentos para lidar com as novas tecnologias, além de enfatizar que as melhorias advindas I4.0 não gerarão demissões para atividades que se tornarão obsoletas, mas que serão necessários a realocação e busca de novas oportunidades de negócios. Isto porque, de acordo com Womack, (1996), os projetos de melhoria geralmente falham se os funcionários sentem que seu trabalho está sendo ameaçado e se tornando redundante para a organização. Wong, Wong e Ali (2009); Jadhav, Mantha e Rane (2014) apontam que esse problema está presente no LP, sendo uma barreira para sua implementação. Jagdish e Mantha (2014) apontam, através de uma revisão sistemática da literatura, que as práticas Lean relacionadas a pessoas (práticas leves) são as principais barreiras para a implementação do PL nas organizações. Oliveira, Sá e Fernandes (2017) reforçam que a implementação bem-sucedida do I4.0 nas organizações dependerá da maturidade no conhecimento das aplicações das ferramentas de LP.

1.3.3 Justificativa estratégica

Para estar preparado para a quarta revolução industrial, o governo alemão estabeleceu seu plano estratégico para a implementação da I4.0. (KAGERMANN et al., 2013; BRANGER e PANG, 2015; LI, 2018), a fim de manter sua competitividade industrial (YIN, STECKE e LI, 2018). A Alemanha é reconhecida mundialmente pela qualidade de seus produtos e serviços, bem como por sua força no campo da automação e eletrônica (LI, 2018). Através de uma pesquisa realizada pela PWC em 2013, é mostrado que 20% das empresas alemãs já estavam envolvidas com a indústria 4.0 (IVANOV et al., 2016). É evidente que esse envolvimento comercial pode ser uma das principais causas que afetam a produção científica da I4.0, pois é o país que mais contribuiu para o mundo científico na área, por meio de publicações na revista Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb (ZWF). De acordo com um estudo do Boston Consulting Group em 2015, estima-se que o esforço da Alemanha para desenvolver o I4.0 aumentará o setor manufatureiro em 90 a 150 bilhões de euros, aumentando a produtividade em 5 a 8% e aumentando a empregabilidade em 6% e o PIB em 1% (GU et al., 2018).

O segundo no ranking de publicações é a China, que criou o plano "Made-in-China 2025" que, como o "Industry 4.0" da Alemanha, visa empregar a digitalização da produção usando tecnologias como sistemas ciber-físicos, Internet das Coisas, e fabricação inteligente (LI, 2018; YIN, STECKE e LI, 2018). Embora a Alemanha esteja em primeiro lugar no número de publicações, são os pesquisadores chineses que têm o maior número de contribuições para o campo de estudo da I4.0. Em 2012, a China assumiu a liderança nas operações de fabricação e a o segundo lugar como potência econômica. Em 2015, tinha um PIB de US $ 11 trilhões, representando 3,27 a mais que o da Alemanha. De fato, a China planeja ser uma das potências de produção global até 2025 (L1, 2018). Olhando para 2015 em comparação a 2002, os investimentos de pesquisa e desenvolvimento da China aumentaram 1000%; o número de patentes aumentou 1912,6%; o número de graduados aumentou 282 vezes e o número de talentos enviados para estudar em outros países (os estudantes que retornaram para o exterior) aumentou 2190% (LI, 2018). Esses dados demonstram o compromisso do governo chinês com a educação e a preocupação com o futuro da economia. Isso justifica a necessidade de envolvimento político para desenvolver um novo conceito para as tecnologias 4.0 e PE nas organizações.

1.3.4 Justificativa Acadêmica

A demanda por novas habilidades não apenas pressiona as universidades a melhorar seus planos de ensino, mas também incentiva as organizações a desenvolver planos de treinamento de funcionários (PIÑOL et al., 2017). No entanto, as dificuldades na formação da força de trabalho são evidentes nas universidades devido a lacunas na educação (CACCIOLATTI, LEE e MOLINERO, 2017). A implementação dos conceitos I4.0 nas organizações exigirá condições de cooperação não apenas globalmente, mas também regionalmente, fortalecendo o relacionamento entre governo, indústria e universidade (VEZA, GJELDUM e MLADINEO, 2015). Para Etzkowitz e Leydesdorff (2000); Etzkowitz (2002); Etzkowitz e Zhou (2017) essa relação universidade-indústria-governo forma a "tripla hélice" da inovação e do empreendedorismo, que são os pontos críticos para o crescimento econômico e o desenvolvimento social baseado no conhecimento. No entanto, Veza, Gjeldum e Mladineo (2015) destacam uma lacuna no modelo, sendo a falta de uma organização ou instituição que promova a relação universidade-indústria-governo, que pode ser resolvida através da criação de Learning Factorys (LF). As LF são caracterizadas por simplificação seletiva ou redução gradual de processos de produção complexos e em larga escala (KEMÉNY et al., 2016) que são usados como modelos de fábricas reais usadas para educação e treinamento de pessoas (ABELE et al., 2017; ENKE et al., 2018 e SCHALLOCK et al., 2018). Os LFs podem promover as habilidades e competências necessárias para lidar com os conceitos de PE e I4.0, além de gerar novas estruturas e metodologias para implementar os conceitos de PE e I4.0 nas organizações.

1.3.5 Justificativa Empresarial

O uso de ferramentas de LP promove baixos custos de produção, permitindo alcançar resultados com a eliminação de desperdícios de todas as áreas da organização, aumentando a produtividade e a lucratividade, com foco no cliente (OLIVEIRA, SÁ E FERNANDES, 2017). Bauer (2018) destaca que o LP prioriza a satisfação do cliente, no entanto, devido ao aumento da demanda do consumidor, novas tecnologias precisam ser exploradas para reforçar a importância das ferramentas de LP. Segundo Davies, Coole e Smith (2017), essas tecnologias são evidenciadas na I4.0 e a união entre esses conceitos tem suporte mútuo, em que os métodos de PL facilitam a implementação da I4.0 e, da mesma forma, a I4.0 aprimora os conceitos de LP.

A quarta revolução industrial impactará drasticamente as carreiras dos trabalhadores (HIRSCHI, 2018) e trará desafios na esfera social, exigindo que as organizações desenvolvam seus talentos para lidar com a crescente complexidade inerente às novas tecnologias (WITTENBERG, 2016, ENKE et al., 2018). O Profissional 4.0 terá que gerenciar várias atividades de trabalho simultaneamente (MATTSSON et al., 2018). No entanto, Peruzzini e Pellicciari (2017) apontaram estudos que mostram que as capacidades funcionais e cognitivas tendem a declinar após os 30 anos, especialmente entre 45 e 64 anos, e que até 2050 cerca de metade da força de trabalho terá mais de 50 anos, nos países desenvolvidos. Além disso, fatores como regulamentos nacionais, mudanças demográficas, aposentadoria tardia e vida útil mais longa permitem que a população trabalhe mais, o que aumenta a idade da força de trabalho nas organizações (ILMARINEN, 2006; GANZATAIN e ERRASTI, 2016). Portanto, o desenvolvimento de soluções que visam melhorar o entendimento e uso das tecnologias e os conceitos da I4.0 é fundamental para que as organizações tenham sucesso nessa migração. Portanto, as empresas precisam desenvolver seu capital humano de acordo com as novas habilidades exigidas pelo I4.0, de implementar mudanças organizacionais e adotar novas práticas de gerenciamento para garantir o uso eficiente de seus ativos intangíveis (KERGROACH, 2017).

2 LP e I4.0: Revisão da literatura

A relação entre o Lean Production (LP) e a Indústria 4.0 (I4.0) em sistemas de saúde tem atraído atenção significativa de acadêmicos para apoiar pacientes e profissionais de saúde, e mesmo que embora ambos os conceitos representem significados diferentes, o LP e a I4.0 compartilham objetivos comuns (BUER et al., 2018). Essa união pode auxiliar em um dos maiores desafios do LP, sendo a sua implementação, pois as evidências apontam que as empresas têm maior probabilidade de implementar LP quando os níveis atuais de tecnologias 4.0 são altos e o contrário também é verdadeiro (TORTORELLA E FETTERMANN, 2018).

Na área da saúde, essas investigações também começaram a ganhar impulso, já que o conceito de Healthcare 4.0 (H4.0) é um paradigma recente e Lean Healthcare (LH) ainda é imaturo se comparado com a aplicação de LP em outros setores (por exemplo, manufatura, construção, etc.). Nesse sentido, as tecnologias LH e H4.0 também podem ser utilizadas para melhorar o desempenho operacional da cadeia de suprimentos de saúde e a satisfação do paciente (TORTORELLA et al., 2020). No entanto, implantar apenas novas tecnologias pelo setor de saúde não será suficiente (POKSINSKA, 2010).

Desta forma, a implementação de técnicas enxutas nos processos operacionais do setor de saúde é vital, pois irá maximizar ainda mais o desempenho operacional, eliminando desperdícios e as atividades que não agregam valor (TORTORELLA et al., 2020). No entanto, as evidências atuais destacam a falta de colaboração entre acadêmicos e profissionais de saúde, o que cria uma lacuna na literatura para compreender os principais fatores estratégicos da transformação digital na cadeia de valor do setor de saúde (GHOSH et al., 2018). Além disso, a literatura apresenta uma limitação do conceito de H4.0 em relação a várias tecnologias existentes já utilizadas em sistemas de saúde (por exemplo, prontuário eletrônico interconectado e em tempo real de pacientes, customização virtual de gerenciamento de medicamentos, previsão em tempo real baseada em nuvem do paciente, entre outros).

A cadeia de suprimentos da saúde caminha para uma terceira revolução caracterizada pela transformação digital, que obriga as empresas de saúde a se empenharem para aumentar o valor para o paciente (o chamado Healthcare 4.0) (DOHAN et al., 2020; JAYARAMAN et al., 2020). O H4.0 é um conceito derivado da I4.0 e representa a transformação dos modelos de negócios de saúde em direção ao gerenciamento orientado a dados (JAYARAMAN et al., 2020). Essa mudança de paradigma é suportada pelo uso de tecnologias de informação em saúde (inicialmente, infraestruturas de rastreamento digital de complexidade em evolução, seguido por registros eletrônicos de saúde, sistemas vestíveis e implantáveis e, mais recentemente, nuvem, neblina e computação de ponta com inteligência artificial). Tais tecnologias beneficiam o setor da saúde, maximizando os benefícios para os pacientes, contribuindo para a qualidade da saúde (Maillet et al., 2018; Kindle et al., 2019) determinando como os tratamentos e intervenções clínicas podem ser apoiados, como os pacientes e profissionais de saúde podem experimentar uma tomada de decisão aprimorada, bem como aumentar a precisão no diagnóstico e o gerenciamento de vários processos de saúde (BATES et al., 2014; GHASSEMI et al., 2015; MANOGARAN et al., 2018).

Embora as tecnologias H4.0 pareçam trazer diversos efeitos positivos para o setor de saúde, o fato de apenas implantar a automação falha se a cultura organizacional não estiver preparada em termos de eliminação de desperdícios e satisfação do cliente (BUER et al., 2018; FURSTENAU et al., 2020). Essa perspectiva está alinhada com a citação de Bill Gates "*A primeira regra de qualquer tecnologia usada em um negócio é que a automação aplicada a uma operação eficiente aumentará a eficiência. A segunda é que a automação aplicada a uma operação ineficiente aumentará a ineficiência*" (BUER et al., 2018; FURSTENAU et al., 2020). Com essa perspectiva em mente, pesquisadores têm se esforçado para entender o papel do LP nos sistemas de saúde (o chamado Lean Healthcare), o que proporciona uma perspectiva onde os pacientes são vistos como clientes, movidos por uma necessidade de eficiência organizacional, em medidas como prazos de entrega do paciente, custos devido a desperdícios e melhoria da qualidade (FERREIRA e SAURIN, 2019).

Ao analisar estudos na literatura sobre I4.0, percebeu-se que vários pesquisadores investigaram a ligação entre LP e I4.0 (Kipper et al., 2019b; Furstenau et al., 2020), uma vez que muitas empresas estão lutando para implementar ambos os conceitos, e as evidências atuais mostram que o pensamento enxuto e as tecnologias emergentes se apoiam na prática (KOLBERG et al., 2017; BUER et al., 2018; TORTORELLA e FETTERMANN, 2018; KIPPER et al., 2019b). Esta relação foi investigada devido ao fato de LP ter atingido seu limite (HINES et al., 2004), e se esforça para fornecer uma produção em massa de produtos altamente customizados, ciclos de vida mais curtos do produto, bem como por não usar o máximo de tecnologias da I4.0 como big data, internet das coisas, computação em nuvem, entre outras (KIPPER et al., 2019a). Além disso, o LP apresenta um total de 24 barreiras, sendo as mais relevantes as restrições financeiras, falta de comprometimento, apoio e liderança da alta administração, bem como diferenças culturais e resistência dos trabalhadores. (JADHAV et al., 2014). O mesmo ocorre com as tecnologias H4.0 e, ainda assim, desafios e barreiras ainda precisam ser superados, que incluem a segurança dos registros pessoais de saúde (Chen et al.), altos investimentos (Schaeffer et al., 2017), falta de conjuntos de habilidades relacionadas (Tortorella et al., 2020), infraestrutura de tecnologia da informação adequada (Ajmera e Jain, 2019), entre outros.

3 Metodologia

3.1 Métodos e procedimentos

Para que se desenvolva uma pesquisa, é fundamental definir o método de pesquisa que será utilizado. De acordo com as características do estudo, será possível escolher diferentes modalidades, sendo possível aliar o qualitativo ao quantitativo (GERHARDT et al., 2009). O autor aponta doze tipos de modalidades: pesquisa experimental, bibliográfica, documental, de campo, ex-post-facto, de levantamento, com *survey*, estudo de caso, participante, pesquisa-ação, etnográfica e etnometodológica. Turrioni e Mello (2012) menciona 6 métodos para pesquisas em engenharia de produção: experimental, modelagem e simulação, *survey*, estudo de caso, pesquisa-ação e soft-system methodology. Para esta pesquisa será utilizado o estudo bibliográfico por meio de mapeamentos científicos e *survey*.

3.2 Mapeamento científico

Para os mapeamentos científicos, primeiramente serão definidos os critérios de pesquisa como escolha das bases de dados, palavras-chave, períodos, bem como critérios de inclusão e exclusão de documentos. Após é apresentado os métodos do mapeamento científico utilizado nesta pesquisa.

I - Critérios de escolha da base de dados: a base de dados S*copus* será utilizada para os mapeamentos científicos da I4.0, pois segundo Cobo *et al*. (2011a) a *Scopus* é um dos bancos de dados mais importantes de produção científica, indexadas e permitem a exportação de metadados para análises e bibliometria. Além disso, esse banco de dados possuI todas as revistas com índice *SJR* (*scientific journal rankings*) e *JCR* (*journal citation reports*) e seu fator de impacto. A base de dados *Scopus* também fornece os dados da publicação, o periódico, os autores, números de citações, instituições, países e área de pesquisa (FALAGAS *et al*., 2008; MEHO e YANG, 2007). Já para o mapeamento científico das relações da I4.0 com a sustentabilidade e I4.0 com a PE serão utilizadas as seguintes bases de dados: *scopus, web of science* e *science direct.*

II - Critérios de escolha do período: para os sistemas de PE o livro “A máquina que mudou o mundo”, produzido por Womack, Jones e Roos (1990) é um critério que pode ser utilizado para a escolha do período. Já, Liao *et al.* (2017) salienta que o aparecimento dos conceitos da indústria 4.0 podem ser observados em períodos anteriores a abril de 2011, conforme Rafael, Shirley e Liveris (2014) por meio de discussões e recomendações do governo dos EUA denominado "*Advanced Manufacturing Partnership* (*AMP*)". Porém, o campo de estudo somente começou a atrair atenção após se tornar, segundo Kagermann *et al.* (2013), um entre os dez projetos oficiais do plano de ação da Alemanha "*High-Tech Strategy* 2020" em março de 2012 com o apoio do governo e, a partir de investimentos na área, é que as pesquisas e trabalhos acadêmicos se disseminaram no mundo científico nos próximos anos. Nesta perspectiva como critério de pesquisa definiu-se que o período será de 2011 a 2020.

III - Critérios de escolha dos termos: Além do termo '*lean production' e 'lean manufacturing'* os termos de busca: 'industry 4.0' OR 'industrie 4.0' OR 'the fourth industrial revolution' OR 'the 4th industrial revolution' OR 'smart manufacturing' OR 'smarter manufacturing' OR 'smart production' OR 'smart factory' OR 'smart factories' OR 'smarter factories' OR 'intelligent factory' OR 'intelligent factories' OR 'digital manufacturing' OR 'ubiquitous factory', 'ubiquitous factories' OR 'ubiquitous manufacturing' OR 'real-time factory' OR 'real-time manufacturing' OR 'factory-of-things'. Tais termos foram utilizados nas revisões sistemáticas de Liao et al. (2017) de Strozzi *et al*. (2017), Buer, Strandhagen e Chan (2018); Liao *et al.* (2017). Para relacioná-los será utilizado o conector lógico em inglês *OR* e cada termo estava entre aspas (''), na intenção de buscar o termo completo e não somente trechos de seus termos. Durante os mapeamentos científicos novos termos de busca serão incorporados. Posteriormente definiu-se os termos relacionados à sustentabilidade com o conector lógico "AND": 'sustainability' OR 'sustainable' OR 'sustainab*', os quais foram utilizados em estudos de Aarseth *et al.* (2017) e Zemigala (2019).

O mapeamento científico sobre a I4.0 e PE buscará identificar a evolução dos temas inerentes à força de trabalho na I4.0 e da PE, os possíveis caminhos de pesquisa, os temas que receberam as maiores citações, os temas mais produtivos e os temas com alto impacto científico serão foco deste estudo.

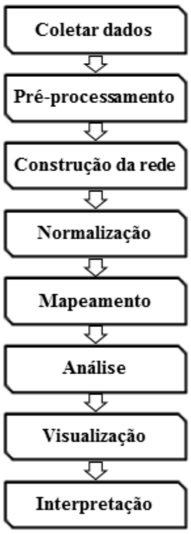
O objetivo do mapeamento científico acerca das relações entre a indústria 4.0 com a sustentabilidade, a fim de descobrir tópicos atuais; autores especialistas na área, criar um mapa do campo de estudo; identificar temas produtivos e com grande impacto científico; descobrir referências, periódicos e palavras-chave importantes para futuras pesquisas na área.

Já no mapeamento científico sobre as relações entre PE e I4.0 serão descritas as principais tecnologias ou pilares da I4.0, como robôs autônomos, manufatura aditiva, internet das coisas, cyber segurança, simulação, *big data analytics*, sistemas integrados, computação na nuvem, realidade aumentada e sistemas ciber-físicos, suas relações com sistema enxuto de produção, ferramentas *lean* e possíveis usos na manufatura avançada para promoção da sustentabilidade.

IV – Filtro e Critérios de escolha dos tipos de documentos: o filtro para encontrar documentos que apresentam algum dos termos de pesquisa no título, resumo e palavra-chave será utilizado a fim de não excluir estudos com relação ao tema proposto. Outro critério a ser utilizado é a escolha do tipo de documento como artigos, artigos *in press* e revisões, estes tipos de documentos garantem que a literatura importante não seja perdida (FREWER et al., 2013).

V – Critérios de escolha do *software* de bibliometria: Cobo *et al.* (2011b) realizaram um estudo analisando 9 *softwares* de bibliometria existentes. Os autores evidenciaram que não existia um *software* com capacidade de analisar todos os elementos chave de um mapeamento científico, o que forçava pesquisadores a utilizarem vários *softwares* para realizar uma bibliometria completa. Nesta perspectiva, Cobo *et al.* (2012) desenvolveram o *software SciMAT* (*Science Mapping Analysis Software Tool*), cujas características são: o processo completo da bibliometria, gratuito para *download* e que permite a incorporação de métodos, algoritmos e medidas para todas as etapas do mapeamento científico, desde o pré-processamento até a visualização dos resultados. (GUTIÉRREZ-SALCEDO *et al.*, 2018; MONTERO-DÍAZ *et al.*, 2018). Além disso, nesta pesquisa será utilizada a abordagem desenvolvida por Cobo *et al.* (2011a), a qual pode ser verificada em estudos de Cobo *et al.* (2014) e De Souza Cavalcanti (2016), Castillo-Vergara, Alvarez-Marin e Placencio-Hidalgo (2018), Montero-Díaz *et al.* (2018), entre outros. A figura 4 apresenta o mapeamento cientifico realizado neste estudo.

Figura 1 - Estrutura do mapeamento científico.



Fonte: Cobo *et al.* (2012).

O método para realizar os mapeamentos científicos vai acontecer em 4 fases que são:

1º etapa – Detecção de temas de pesquisa: nesta etapa serão utilizados os documentos coletados conforme prevê a estrutura do mapeamento científico. Os itens analisados serão palavras-chave e a extração das informações relevantes será a partir da frequência de coocorência (*co-occurence*) das palavras-chave, ou seja, quantidade de documentos em que as palavras aparecem juntas (CALLON *et al*., 1983). Para o cálculo de similaridade será utilizado o índice de equivalência (*equivalence index*) o qual calcula a força de ligação entre os *clusters* (CALLON, COURTIAL e LAVILLE, 1991). O algoritmo *clustering* utilizado para detecção dos temas será o algoritmo dos centros simples (*simple center algorithm*), o qual demonstra a força de ligação entre *clusters* (COULTER, MONARCH e KONDA 1998). Além disso, se necessário será aplica uma redução de dados, caso ocorra uma grande quantidade de palavras-chave identificadas.

2º etapa – Visualização de temas e ligações temáticas: Os temas obtidos através dos clusters foram plotados em diagramas bidimensionais que possuem quatro quadrantes, baseados em valores de densidade (eixo y) e centralidade (eixo x). A densidade mede a força interna de ligação e pode ser definida como d=100(Σeij/w), onde i e j são palavras-chave pertencentes ao tema e w é o número de palavras-chave no tema, enquanto que a centralidade mede a intensidade da ligação de um cluster com outros clusters, , pode ser definido como c=10*Σekh, onde k é uma palavra-chave pertencente ao tema eh é uma palavra-chave pertencente a outros temas (CALLON, COURTIAL e LAVILLE, 1991; LÓPEZ-ROBLES et al., 2019). Neste contexto, os temas de pesquisa podem ser classificados em quatro grupos (figura 5):

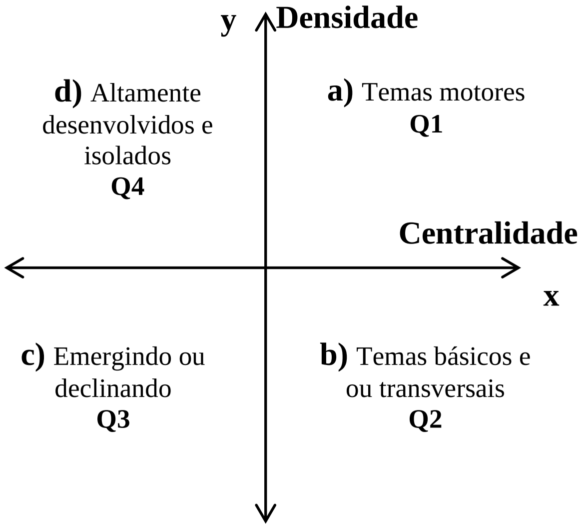
a) ***Temas motores*** (Primeiro quadrante, **Q1**): alta centralidade e densidade (temas importantes para o campo de pesquisa com alto desenvolvimento).

b) ***Temas básicos e transversais*** (Segundo quadrante, **Q2**): Alta centralidade e baixo desenvolvimento (tendem a se tornar temas motores futuramente devido sua alta centralidade).

c) ***Temas emergentes ou declinando*** (Terceiro quadrante, **Q3**): baixa centralidade e densidade (necessidade de análise qualitativa para definir se está emergindo ou declinando).

d) ***Altamente desenvolvidos e temas isolados*** (Quarto quadrante, **Q4**): baixa centralidade e alto desenvolvimento (deixaram de ser importantes devido um novo conceito ou tecnologia).

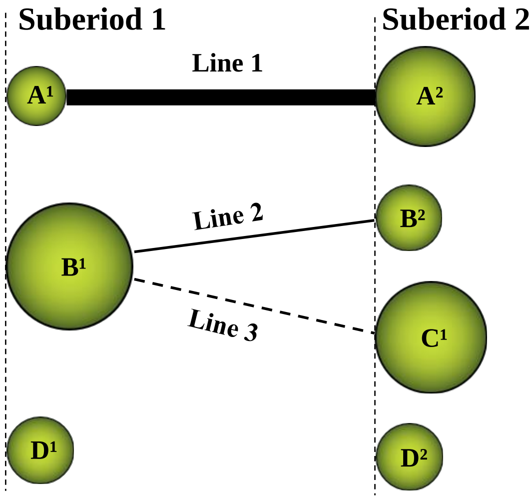
Figura 2 - Diagrama estratégico.



Source: Cobo *et al.* (2012).

3º etapa – Descoberta de áreas temáticas: nesta etapa será analisada a evolução dos temas de pesquisa a fim de evidenciar as principais áreas que evoluíram no campo de pesquisa em um determinado período de tempo, identificar origens, bem como as inter-relações. Para tanto, será preciso construir um mapa de evolução com o índice de inclusão (*inclusion index*). A figura 6 apresenta um exemplo da evolução temática. A linha sólida (linha 1 e 2) significa que os *clusters* conectados (A^1 e A^2; B^1 e B^2) compartilham o tema principal, enquanto a linha tracejada (linha 2) caracteriza que os *clusters* (B^1 e C^1) compartilham elementos que não são tema principal e quando não existe linha significa descontinuidade (D^1) e D^2 é um novo *cluster*. A espessura das bordas é proporcional ao índice de inclusão, e o volume das esferas é proporcional ao número de documentos publicados associados com cada *cluster* (COBO *et al.*, 2012).

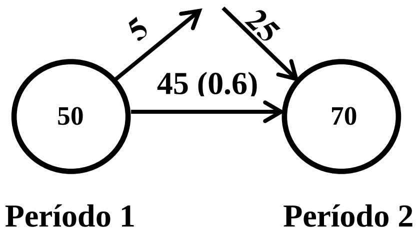
Figura 6 – Exemplo de evolução temática.



Fonte: Cobo et al. (2012).

Ainda na terceira fase, será possível analisar a sobreposição geral (*general overlapping*), conforme exemplo na figura 7. Os círculos representam os períodos e seu número de itens (neste caso palavras-chave). A seta horizontal representa o número de palavras-chave compartilhadas entre os períodos 1 e 2, o índice de estabilidade (iE) entre eles é mostrado entre parênteses. A seta de entrada superior representa o número de novas palavras-chave em Período 2, e a seta de saída superior representa àquelas que são apresentados no Período 1, mas não no Período 2 (COBO *et al.*, 2012).

Figura 3 - Sobreposição geral.



Fonte: Cobo *et al.*, (2012).

4º etapa - Análise de performance: Nesta etapa, a contribuição de todo o campo de pesquisa será medida (quantitativamente e qualitativamente), a fim de identificar a qualidade dos *clusters* e estabelecer as subáreas mais produtivas e de maior impacto. Além disso, serão utilizados alguns indicadores bibliométricos como número de publicações, número de citações e *h-index* proposto por Alonso *et al.* (2009).

Etapa de pré-processamento dos dados para bibliometria

Os dados obtidos das bases de dados frequentemente apresentam erros, logo é necessário realizar um pré-processamento a fim de garantir resultados de qualidade (COBO *et al.*, 2012). Primeiramente**,** serão exportados os documentos selecionados para análise bibliométrica da base de dados *Scopus.* Após, será realizada a etapa do pré-processamento por meio da exclusão de duplicações de autores, referências, palavras-chave, documentos. Além disso, palavras muito amplas como “industry 4.0” ou sem sentido como “C#” serão excluídas. Da mesma forma, palavras com erros ortográficos serão corrigidas. Por fim, algumas palavras-chave serão agrupadas por representarem o mesmo conceito como, por exemplo, *“Internet of Things*” e “*IoT*”.

O desenvolvimento do mapeamento científico desta pesquisa se dará no período: (2011 – 2020) e será dividida em 04 subperíodos respectivamente: 2011 – 2014, 2015 - 2016 2017 - 2018 e 2019 - 2020.

3.3 *Survey* para identificar as relações de LP e I4.0 na performance operacional em sistemas de saúde

Nesta etapa, pretende-se identificar por meio de *survey* os efeitos da união dos conceitos de I4.0 e LH no desempenho operacional de sistemas de saúde. Para tanto, será realizado o método utilizado por Tortorella e Fettermann (2018) com questionários adaptados aos sistemas de saúde por Tortorella e Fettermann (2018) e Tortorella et al. (2019) para questões relacionadas ao LH (tabela 1) e Tortorella et al. (2020) para questões referentes ao H4.0 (Tabela 2). Após será análise a melhoria da performance operacional observada durante os últimos três anos dos sistemas de saúde conforme cinco indicadores: (a) produtividade, (b) nível de serviço na entrega, (c) nível de estoque, (d) segurança do trabalho (acidentes) e (e) qualidade (refugo e retrabalho) (Tabela 3). Uma escala de cinco pontos variando de 1 (piorou significativamente) a 5 (melhorou significativamente) será utilizada no questionário. O método de pesquisa proposto pelos autores possui três etapas: (i) desenvolvimento do questionário e coleta de dados, (ii) agrupamento dos dados (utilizando a análise de variância) e (iii) análise dos dados. Os respondentes deverão ter amplo conhecimento sobre as tecnologias H4.0 e técnicas e conceitos sobre LH.

Tabela 1 – Tecnologias da indústria 4.0 aplicadas em sistemas de saúde.

	Tecnologias 4.0 aplicadas em saúde
P1	Utilização de inteligência artificial e técnicas de aprendizagem de máquina para auxílio em tomada de decisão clínica.
P2	Suporte interconectado de emergência médica.
P3	Consultas realizadas de forma remota e elaboração de planos de atendimento em tempo real.
P4	Procedimentos cirúrgicos e clínicos assistidos remotamente.
P5	Nutrição remota e gerenciamento de infusão.
P6	Cuidado digital não invasivo.
P7	Tecnologias de realidade virtual para suportar decisões clínicas.
P8	Sistema de rastreabilidade de dispositivos médicos.
P9	Plataformas digitais para compartilhamento colaborativo de dados e informações de pacientes.
P10	Geração de informações médicas sintéticas por meio da computação em nuvem.
P11	Projeto assistido por computador de dispositivos médicos modulares e personalizados.

Tabela 2 – Conceitos e técnicas de LP aplicadas em sistemas de saúde.

LH - Construtos operacionais	Técnicas lean aplicadas em saúde
Comunicação com fornecedores	P1 - Disponibilizamos feedback aos nossos fornecedores sobre qualidade e desempenho de entrega.
	P2 - Empregamos esforços para estabelecer relacionamentos de longo prazo com nossos fornecedores.
	P3 - Os fornecedores estão diretamente envolvidos no processo de desenvolvimento de novos serviços e melhoria de processos.
Entrega JIT	P4 - Nossos principais fornecedores entregam seus produtos com base no JIT.
	P5 - Temos um programa formal de certificação de fornecedores.
	P6 - Nossos fornecedores estão contratualmente comprometidos com reduções de custos anuais.
Desenvolvimento de fornecedores	P7 - Nossos fornecedores estão contratualmente comprometidos com a redução anual de custos.
	P8 - Nossos principais fornecedores estão localizados nas proximidades de nosso sistema de saúde.
	P9 - Temos comunicação em nível corporativo sobre questões importantes com os principais fornecedores.
	P10 - Tomamos medidas ativas para reduzir o número de fornecedores em cada categoria.
	P11 - Nossos principais fornecedores gerenciam nosso estoque.
	P12 - Avaliamos os fornecedores com base no custo total e não por preço unitário.
Envolvimento com clientes/pacientes	P13 - Estamos frequentemente em contato próximo com nossos clientes/pacientes.
	P14 - Nossos clientes/pacientes nos dão feedback sobre qualidade e desempenho dos nossos serviços e processos.
	P15 - Nossos clientes/pacientes estão ativamente envolvidos nas ofertas de serviços e produtos atuais e futuros.
	P16 - Nossos clientes/pacientes estão diretamente envolvidos nas ofertas de serviços e produtos atuais e futuros.
	P17 - Nossos clientes/pacientes frequentemente compartilham informações de demanda atuais e futuros com nosso departamento de marketing.
Sistema puxado	P18 - Os serviços são puxados pelos clientes/pacientes.
	P19 - As atividades dos processos são puxadas pela demanda atual da próxima atividade.
	P20 - Usamos um sistema de serviços puxados.
	P21 - Usamos Kanban, quadrados ou recipientes de sinais para controle das atividades.
Fluxo	P22 - Os clientes/pacientes são classificados em grupos com requisitos de processamento semelhantes.

	P23 - Os clientes/pacientes são classificados em grupos com requisitos de roteamento semelhantes.
	P24 - O equipamento é agrupado para produzir um fluxo contínuo de clientes/pacientes.
	P25 - Classificação de clientes/pacientes determinam nosso layout de atendimento.
Set-up baixo	P26 - Nossos funcionários praticam configurações para reduzir o tempo necessário das máquinas.
	P27 - Estamos trabalhando para reduzir os tempos de preparação em nosso sistema de saúde.
	P28 - Temos baixos tempos de configuração dos equipamentos em nosso sistema de saúde.
Controle de processos	P29 - Grande número de equipamentos / processos no sistema de saúde estão atualmente sob Controle Estatístico de Processo (CEP).
	P30 - Uso extensivo de técnicas estatísticas para reduzir a variância do processo.
	P31 - Gráficos que mostram taxas de erros são usados como ferramentas no sistema de saúde.
	P32 - Usamos diagramas de tipo espinha de peixe para identificar as causas dos problemas de qualidade.
	P33 - Conduzimos estudos de capacidade do processo antes do lançamento do serviço ser colocado em prática.
Envolvimento dos colaboradores	P34 - Os profissionais de saúde são essenciais para as equipes de solução de problemas.
	P35 - Profissionais de saúde conduzem programas de sugestões.
	P36 - Profissionais de saúde lideram esforços de melhoria de serviços / processos.
	P37 - Profissionais de saúde passam por treinamento multifuncional.
Manutenção preditiva	P38 - Dedicamos uma parte do dia a dia para atividades relacionadas à manutenção planejada de equipamentos.
	P39 - Realizamos a manutenção de todos os nossos equipamentos regularmente.
	P40 - Mantemos registros de todas as atividades relacionadas à manutenção de equipamentos.
	P41 - Publicamos registros de manutenção de equipamentos de saúde nos setores para compartilhamento ativo com empregados.

Tabela 3 – Questões relacionadas à performance operacional de sistemas de saúde.

	Análise da performance operacional
P1	Tivemos melhoria da produtividade.
P2	Obtivemos maior nível deficiência em atendimentos de clientes/pacientes.
P3	Conseguimos ter um controle maior do nosso estoque.
P4	Maior segurança dos trabalhos (acidentes).
P5	Aumentamos o nível de qualidade (refugo e retrabalho).

4 ARTIGO 1 – Scopus scientific mapping production in industry 4.0 (2011–2018): a bibliometric analysis

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Abstract

Research in industry 4.0 is growing, driven by the innovations in production systems on a continuous basis. In this study, we identified the evolution of themes inherent in the industry 4.0 using a bibliometric software, namely SciMAT (Science Mapping Analysis Software Tool). The analyses included 1882 documents, 4231 keywords, and the relevant information was extracted based on frequency of co-occurrence of keywords. The clusters were plotted in two-dimensional strategic diagrams and analysed using the bibliometric indicators such as the number of publications, number of associated documents, and h- index. The results revealed that 2017 had the largest number of publications. Expert authors in thefield and the periodicals that published the most were identified. The science mapping presented 31 clusters in which the most representative motor themes were CPS (Cyber-Physical System), IoT (Internet of Things), and Big Data. In addition, it was possible to identify fields with high investment of efforts by the scientific community such as the union between lean production and industry 4.0, production-centered CPS (CPPS), IoT (Industrial Internet of Things - IIoT), among others. The overlapping map showed an increase in the number of keywords from 338 to 1231 over the period of data. The map of scientific developments supported by an exhaustive research, it was possible to show the state of the art, the main challenges and perspectives for future research in thefield of industry 4.0 such as Technology, Collaboration/Integration, Management and Implementation.

Keywords: Industry 4.0; smart manufacturing; bibliometrics; scientific mapping; the fourth industrial revolution

Introduction

The fourth industrial revolution known as industry 4.0 was predicted and recognised as the era of smart factories (Drath and Horch 2014; Kagermann et al. 2013; Lasi et al. 2014). This revolution is gaining increasing attention from academics and professionals owing to the innovations in manufacturing systems (Strozzi et al. 2017). A systematic literature review of Liao et al. (2017) investigated the enabling features of industry 4.0; researchers working on thefield; the main research directions and the current research efforts and the existing industry 4.0 application fields. Thoben, Wiesner, and Wuest (2017) analyzed the landscape of industry 4.0 and smart manufacturing focused on cases of applications to improve internal logistics, safety of human-robot interaction and operational data from an aircraft, they also identified research issues from the cases and listed in three main categories: technological, methodological and business case, contributing significantly to new perspectives and for future research in industry 4.0. Hozdic´ (2015) contributed by pointing the way to industry 4.0, its main technologies and ways of implementation. Pereira and Romero (2017) identified and compared the visions and theories of the main studies related to industry 4.0; the impact of the main technological developments; the most important innovations, trends and challenges, as well as an analysis of the impact of consequences on the industrial, economic and social aspects. Oztemel and Gursev (2018) carried out an exhaustive literature review to develop a clear definition of industry 4.0, to understand the progress of the subject, and to create a road map for business digitisation. Through a combination between systematic literature review and bibliometric analysis, with the support of Sci2 Tool software, Strozzi et al. (2017) analyzed the scientific evolution field of research of 'Smart Factory' and highlighted the research directions for thefield, including the critical areas for development, as well as the trends and emerging topics for future research. In this context, to contribute to the research in continuation to the evidenced studies, this article has multifold objectives: (1) to identify the evolution of themes inherent in the industry 4.0, the possible research paths, the subjects that received the highest citations, the most productive subjects, and the issues with high scientific impact; (2) to discover current topics and expert authors in the field; (3) to create a map of the field of study; and (4) to discover the references, journals, and keywords for future research in the field. To carry out this science mapping, the SciMAT software developed by Cobo et al. (2012) was used.

The bibliometric analysis has two objectives in exploring afield of research: analysis of the mapping and analysis of academic performance (Cobo et al. 2012). According to Morris and Van Der Veer Martens (2008) and Cobo et al. (2014), science mapping is a robust bibliometric technique to understand and monitor the structure and evolution of thefield of research in order to identify how authors, disciplines, and studies are related to one another, while the performance analysis helps capture the effectiveness of the scientific documents based on citations.

The rest of this article is organised as explained here. Section 2 comprises the materials and methods used with definitions, research criteria, and bibliometric analysis. Section 3 presents the studies on industry 4.0 and related articles, as well as the bibliometric analysis of the selected documents together with a detailed discussion on the data. Section 4 presents the analysis of thematic areas. Section 5 presented an exhaustive research in the articles published in International Journal of Production Research to develop the state of the art and demonstrate the main challenges and perspectives in industry 4.0.

Materials and methods

The materials and methods in line with the objectives of this study are presented here. Firstly, the search criteria for the databases, keywords, and periods, as well as the criteria for inclusion and exclusion of documents are defined. Subsequently, the methods of the science mapping used in this research are presented.

Criteria for choosing the database: The Scopus database was used for this science mapping. According to Cobo et al. (2011a), Scopus is a well-organized, indexed database of scientific production with provisions for export of metadata. It includes all journals with SJR (Scientific Journal Rankings), JCR (Journal Citation Reports), and their impact factors. Furthermore, it provides publication data, periodicals, authors, citation numbers, institutions, countries, and research area (Falagas et al. 2008; Meho and Yang 2007).

Criteria for choosing the period: although Cobo et al. (2018) has performed a bibliometric analysis of reviews in the research field of industry 4.0 in the period 2013–2018 in web of science database, Liao et al. (2017) asserts that the emergence of industry 4.0 concepts can be traced back to a period before April 2011. According to Rafael, Shirley, and Liveris (2014), there were lively discussions and recommendations on this in US government circles during the launch of advanced manufacturing partnership (AMP); however, the field of study began to attract attention only after becoming, according to Kagermann et al. (2013), one among the ten projects of the German action plan ‘High-Tech Strategy 2020’ in March 2012. Eventually, the research and academic activities have spread in the scientific world. Although the year 2011 presents only 3 documents, the authors described concepts and technologies related to industry

4.0 such as nanotechnology (Parthasarathi and Thilagavathi 2011), smart city, smart factories (Oda et al. 2011), smart grid and Internet of Things (Wang et al. 2011). In this perspective, as a criterion, the data period identified for analysis in this research was 2011–2018.

Criteria for choosing terms: The search terms were identified as ‘industry 4.0’, ‘the fourth industrial revolution’, ‘the 4th industrial revolution’, ‘smart manufacturing’, ‘smart production’, ‘smart factory’, and ‘smart factories’. These terms were used by Buer, Strandhagen, and Chan (2018), and Liao et al. (2017). The logical operator ‘OR’ was used to relate the terms. Each term was placed between quotation marks (‘‘), when the search was for the complete term instead of only the excerpts. The date of retrieve of data from Scopus database was in 21/08/2018. In this research only the broad words about industry 4.0 were used, therefore words such as ‘cyber physical system’, ‘cyber physical production system’, ‘Internet of things’, ‘industrial internet’, ‘big data’, etc, were not used.

Criteria for choosing the types of document: A filter was used to find the documents having the search terms in the title, abstract, and keyword to ensure that a study related to the proposed topic was not excluded. Another criterion used was the type of the document such as articles in press and reviews to ensure that an important literature was not excluded (Frewer et al. 2013).

Criteria for choosing bibliometrics software: Cobo et al. (2011b) conducted a study analysing 9 bibliometrics soft- ware (Bibexcel, CiteSpace, CoPalRed, IN-SPIRE, Leydesdorff’s Software, Network Workbench Tool, Science of Science Tool, VantagePoint and VOSViewer) and none of these were found to be capable of analyzing all the key elements of a science mapping (data retrieval, preprocessing, network extraction, normalisation, mapping, analysis, visualisation, and interpretation). As a result, several software tools has to be used by researchers in order to perform a deep science map- ping analysis. Therefore, Cobo et al. (2012) developed the SciMAT software, free for download, with complete bibliometry process and provisions to incorporate methods, algorithms, and measurements for all stages of science mapping from pre- processing to visualisation of the results (Gutiérrez-Salcedo et al. 2018; Montero-Díaz et al. 2018). The present research used the approach developed by Cobo et al. (2011a) that could be verified in a number of studies that include Cobo et al. (2014), Castillo-Vergara, Alvarez-Marin, and Placencio-Hidalgo (2018), and Montero-Díaz et al. (2018). Figure 1 shows the mapping performed in this study. The method to perform the bibliometry occurs in 4 phases that are explained in the following sections.

Figure 1. Workflow of science mapping. Source: Cobo et al. (2012).

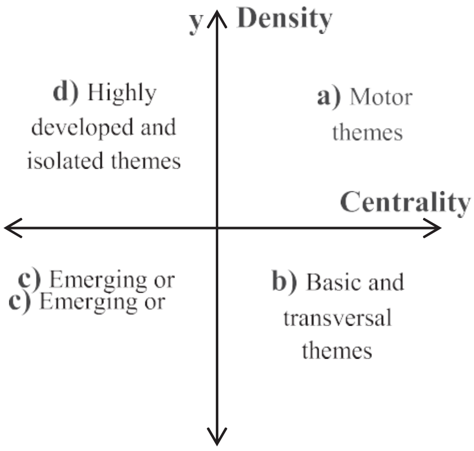

Figure 2. Strategic diagram. Source: Cobo et al. (2012).

Detection of research themes: In this phase, all the 1882 documents included for bibliometric analysis were used. The keywords were analysed, and the documents with co-occurrence of the keywords were extracted. In other words, the number of documents in which the keywords appear together (Callon et al. 1983; Cobo et al. 2014) was studied. For the similarity calculation, an equivalence index that calculates the binding force between the clusters (Callon, Courtial, and Laville 1991; Cobo et al. 2014) was used. A simple centre algorithm that demonstrates the strength of the link between clusters (Cobo et al. 2011a; Coulter, Monarch, and Konda 1998) was used as the clustering algorithm to detect the themes. In addition, a reduction of data was required due to a large number of keywords identified. This data reduction was carried out in order to select the most important/representative data, for this, we selected only keywords with a minimum of 10 associated documents. In addition, for the construction of the network was used the configuration of maximum cluster size: 25 and minimum cluster size: 1.

Topics and thematic links: The themes obtained through the clusters were plotted in bi-dimensional diagrams that have four quadrants based on the values of density (y-axis) and centrality (x-axis). The density measures the internal binding force, while the centrality measures the strength of the binding of a cluster to other clusters (Callon, Courtial, and Laville 1991). In this context, the research topics can be classified into four groups: a) Motor themes, b) Basic and transversal themes, c) Emerging or declining themes, and d) Highly developed and isolated themes. Each group is plotted in a quadrant as shown in Figure 2. The diagram is also known as strategic or Callon diagram (Callon, Courtial, and Laville 1991; Cobo et al. 2012).

Discovery of thematic areas: In this phase, the evolution of the research themes was analysed to identify their fields of research, period of time, origins, and interrelationships. For this purpose, thematic evolution maps with the inclusion index were constructed. Figure 3 shows a typical map. The solid line (lines 1 and 2) indicates that the connected clusters (A^1 and A^2, B^1 and B^2) share the main theme (name of main theme   thematic nexuses), the dashed line (line 3) characterises that the clusters (B^1 and C^1) share elements that are not the main themes (name of main theme thematic nexuses), and the absence of a line means discontinuity (D^1 and D^2, D^2 being a new cluster). The thickness of the lines is proportional to the inclusion index, and the volume of the spheres is proportional to the number of published documents associated with each cluster (Cobo et al. 2012). In the third phase, the overlapping map were analysed as shown in Figure 4 and in the example as shown in Table 1. The circles represent the periods with the respective number of keywords. The horizontal arrow represents the number of keywords shared between the periods 1 and 2, while the stability index (% of keywords shared) between them is shown in parentheses. The top incoming arrow represents the number of new keywords in period 2, and the top outgoing arrow represents those displayed in period 1 but not in period 2 (Cobo et al. 2012).

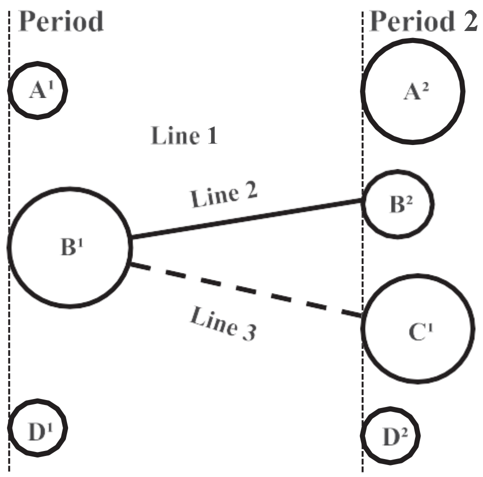

Figure 3. Evolution example. Source: Cobo et al. (2012).

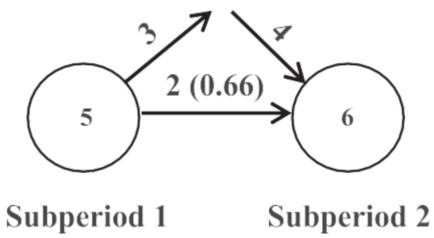

Figure 4. Overlapping map. Source: Cobo et al. (2012).

Table 1. Example of overlapping map

Keywords from the Subperiod 1			Keywords from the Subperiod 2	
Used	Lost	Shared	New	Used
5	3	2 (0.66%)	4	6
Industry Company Data Robotics Factory	Company Data Factory	Industry Robotics	Software Human Decision Machine	Industry Robotics Software Human Decision Machine

Performance analysis: In this phase, the contribution of the entire field of research was measured (quantitatively and qualitatively) to evaluate the quality of the clusters and establish the most productive and high-impact subareas. In addition, we used some bibliometric indicators such as the number of publications, number of citations, and h-index proposed by Alonso et al. (2009).

Preprocessing of data for bibliometrics: The data obtained from the databases often contain errors; therefore, a pre- processing is performed to ensure quality results (Cobo et al. 2012). First, the 1882 documents (4231 keywords) selected for the bibliometric analysis of the Scopus database were exported. Subsequently, the preprocessing step was performed by excluding duplications of authors, references, keywords, and documents. Similarly, broad words like ‘industry 4.0’ or garbage-like data such as ‘C#’ were excluded, and misspelled words were corrected. Finally, the keywords representing the same concept such as ‘Internet of Things’ and ‘IoT’ were grouped. The science mapping developed for 2011–2018 was divided into four subperiods: 2011–2015, 2016, 2017, and 2018.

Analysis of data and discussions

The first four years were grouped as a single subperiod due to fewer publications (Figure 5). The number of publications for the four subperiods was 270, 372, 664, and 576, respectively.

The number of articles related to industry 4.0 was less in the initial years; however, it tripled in subsequent years until 2016; It attained the peak (664) in 2017 followed by a decline in 2018 as there are several articles pending to be published owing to the realisation of this study (August 2018).

The journals that published the studies related to industry 4.0 are presented in Figure 6 along with the respective number of publications: ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb (130), Procedia Manufacturing (109), IEEE Access (48), WT Werkstattstechnik (47), IFAC-PapersOnLine (46), Productivity Management (46), and so on.

Authors (Figure 7) who published more articles in thisfield are Li, D. (25), Wan, J. (17), Zhang, Y. (16), Wang, S. (15), Tao, F. (15), Liu, C. (14), Zhang, C. (11), Metternich, J. (11), Wang, J. (10), and Rauch, E. (10).

The number of publications in Scopus over time shows a high growth rate, which demonstrates the importance and relevance of industry 4.0 to the scientific world. Germany is the leader of publications, following by China, United States, Italy and South Korea. Germany is the country recognised with the most developed industrial automation sector in the world (Rüßmann et al. 2015). To be prepared for the fourth industrial revolution, Germany established its strategic plan to implement industry 4.0 (Branger and Pang 2015; Kagermann et al. 2013; Li 2018) in order to maintain its industrial competitiveness (Yin, Stecke, and Li 2018). Germany is recognised worldwide for the quality of its products and services, as well as for strength in thefield of automation and electronics (Li 2018). Research by a survey carried out by the PWC Company indicates that in 2013, 20% of German companies were already involved with industry 4.0 (Ivanov et al. 2016). It is evident that this entrepreneurial involvement may be one of the main causes that affect the scientific production of industry 4.0 in the country, because as can be seen in Figure 8 it is the country that contributes most to the scientific environment through publications in the journal ZWF (Figure 6). According to a study by the Boston Consulting Group in 2015, it is estimated that Germany's effort to develop the industry 4.0 will boost the manufacturing sector by 90–150 billion Euros, increasing productivity by 5–8%, as well as increasing of employability by 6% and GDP by 1% (Gu et al. 2019).

The second in the ranking is China that created the 'Made-in-China 2025' plan, similarly to the 'Industry 4.0' from Germany, this plan aims to employ manufacturing digitisation, Cyber-Physical Systems, Internet of Things, and intelligent manufacturing (Li 2018; Yin, Stecke, and Li 2018). Although Germany ranked first in the number of publications, it is the Chinese researchers who hold the highest number of contributions to the field of study (Figure 7). In the year of 2012, China gained the leadership in manufacturing operations and the second largest economic power, and in 2015 had the GDP of $ 11 trillion, representing 3.27 greater than that of Germany, they also plan to be one of the global manufacturing powers by the year 2025 (Li 2018). When analyzing the year 2015 compared to 2002, China's investments in research and development increased by 1000%; the number of patents increased by 1912.6%; the number of graduates increased by 282 times and the number of talents sent to study abroad increased by 2190% (Li 2018). These data demonstrate the Chinese government's engagement with education and concern for the future of the economy. In this way, the number of high-level publications of Chinese researchers in thefield of research of industry 4.0 (Figure 7) is justified.

Following, the strategic diagrams of thefield of research, which classify the clusters according to their centrality and density, will be analyzed. The centrality measures for a given cluster the intensity of its links with other clusters. The more numerous and stronger these links are, the greater their importance for thefield of research studied. Thus, the cluster is a necessary point of passage and essential for any interested person to invest efforts in the associated clusters, directly or indirectly (Callon, Courtial, and Laville 1991; Cobo et al. 2012). The density characterises the strength of the links that tie the clusters together. The stronger these links, the more research problems that correspond to the cluster are coherence and integration. Density provides a good representation of the ability of the subject to maintain and develop over time in the field of research (Callon, Courtial, and Laville 1991; Cobo et al. 2012).

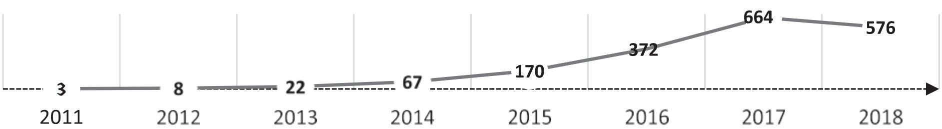

Figure 5. Number of publications in Scopus over time (2011–2018). Source: SciMAT.

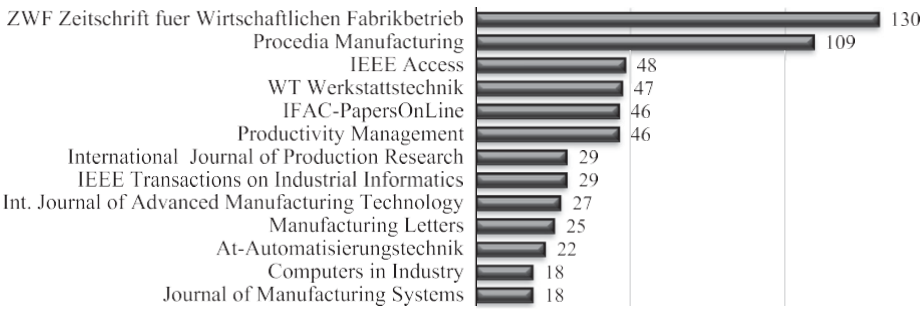

Figure 6. Journals that publish studies related to industry 4.0. Source: SciMAT.

Figure 7. Authors that publish studies related to industry 4.0. Source: SciMAT.

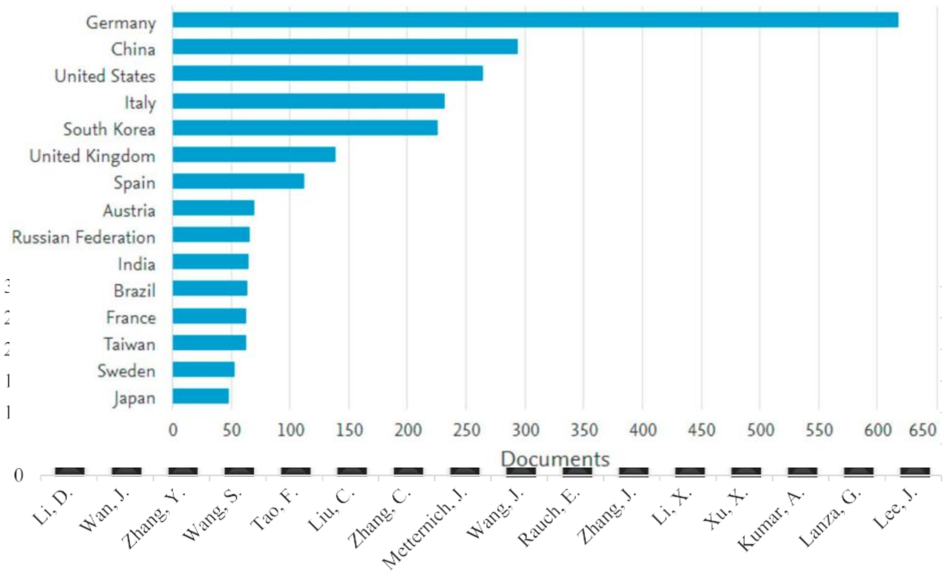

Figure 8. Number of documents per country. Source: Scopus.

Analysis and discussion of the strategic diagram of the second subperiod (2016)

Figure 8(b) shows that the CPS is no longer a motor theme in 2016 as it has become a basic and transversal theme due to its reduced development, but with an increased number of documents (61) and decreased h-index (13). This phenomenon means that, according to Callon, Courtial, and Laville (1991) 'thefield as a whole has become more bottom-up, and that as a result "fundamental" research has developed its ideas and new themes as a response to problems encountered by various technological applications'. The same happens with 'production'; however, the number of documents and h-index remain the same as thefirst sub-period. In contrast, the 'virtualization' becomes an engine theme with medium centrality and density, 3 associated documents, and h-index (2). It comprises studies related to the virtual prototyping of products (Zawadzki and Żywicki 2016), virtual representation of objects (Zezulka et al. 2016), virtualisation of manufacturing execution systems (Morariu et al. 2016), as well as the virtualisation of objects, processes, and factories (Shafiq et al. 2016).

The 'artificial intelligence (AI)' also emerges as a motor theme with 5 associated documents and low h-index (1). Examples of authors in this case are Moreno Munoz (2016) and Brandenburger et al. (2016). The 'innovation' is observed to be a highly developed theme with a centrality below average. Dmitriev et al. (2016) analysed the socio-economic impacts of innovations with regard to the fourth industrial revolution, while Pfeiffer (2016) highlighted the innovations in Germany's educational system in preparing the workforce for industry 4.0.

Analysis and discussions of the strategic diagram of the third subperiod (2017)

Figure 8 (c) shows that 'internet of things (IoT)' is the most prominent cluster for 2017 as it has the highest number of documents (139) and h-index (13). It is considered as a novel internet revolution (Majeed and Rupasinghe 2017). The IoT is a key technology in the industry 4.0 as it allows a real-time interaction with the entire supply chain (Ben-Daya, Hassini, and Bahroun 2017; Zhong, Xu, and Wang 2017) and performance measurement (Hwang et al. 2017).

The 'human factors' is observed to be a cluster with the greatest centrality in this period with 31 documents and an h-index of 4. Studies like those of Peruzzini, Grandi, and Pellicciari (2017); Dombrowski, Stefanak, and Perret (2017); Pacaux-Lemoine et al. 2017, and Robla-Gómez et al. (2017) addressed the relationship between the various demands of industry 4.0 for improved relationships between workers, machines, and systems. These relationships, known as 'centred- human design', are crucial in current manufacturing systems because of two factors: increasing workers due to population aging and increasing complexity in adopting new technologies in manufacturing (Peruzzini and Pellicciari 2017). The fourth industrial revolution will drastically impact the career of workers (Hirschi 2018) and will bring challenges in the social sphere, requiring organisations to develop their talents so that they can cope with the increasing complexity inherent in new technologies (Bokrantz et al. 2017; Enke et al. 2018; Wittenberg 2016). The professional 4.0 will have to manage several work activities simultaneously (Mattsson et al. 2018). However, Peruzzini and Pellicciari (2017) have pointed to studies that demonstrated that both functional and cognitive abilities tend to decline after the age of 30, mainly between 45 and 64, and that by 2050 about half of the workforce will have more 50 years in developed countries. In addition, factors such as national regulations, demographic changes, late retirement and increased life expectancy of the population allow the population to work longer, which in turn increases the age range of the workforce in organisations (Ganzarain and Errasti 2016; Ilmarinen 2006). Therefore, developing solutions that use centred-human design, aimed at facilitating the use and understanding of I4.0 technologies and concepts by workers is fundamental for organisations to succeed in this migration (Figure 9).

The 'decision making' emerges as the most developed theme among the motor themes of 2017, with 13 documents and an h-index of 2. The decision-making activities related to industry 4.0 are identified in studies of Francalanza, Borg, and Constantinescu (2017); Vazan et al. (2017); and Kim (2017). The 'knowledge' visualised in thefirst subperiod (2011– 2015) presents a greater development and 11 associated documents in this subperiod (2017), but with a slight decrease in its centrality. Authors such as Stefan et al. (2017) addressed the challenges for the employees and employers in dealing with new knowledge and technical skills in industry 4.0, while Bernstein et al. (2017) explored the application of the generated knowledge to the decision making on the product life cycles in an intelligent factory. Therefore, the companies are expected to focus on knowledge in the fourth industrial revolution (Götz and Jankowska 2017).

Despite being the low-performance parameters, the ‘real time’ and ‘maintenance’ are clusters with promising themes in the researchfield. An intelligent factory is expected to adapt itself to real-time manufacturing processes (Lu and Ju 2017) and to process a larger database (Syafrudin et al. 2017) realised through IoT that captures real-time data on environment (Xu and Chen 2017).

The ‘maintenance’ is a cluster analysed by several authors; Bokrantz et al. (2017) analysed the expected impacts of industry 4.0 on ‘maintenance’ in an organisation. The ‘prognostics and health management’ (PHM) is closely related to ‘maintenance’ because the PHM enables a systematic approach towards the health of the machines and their maintenance schedules (Xia and Xi 2017).

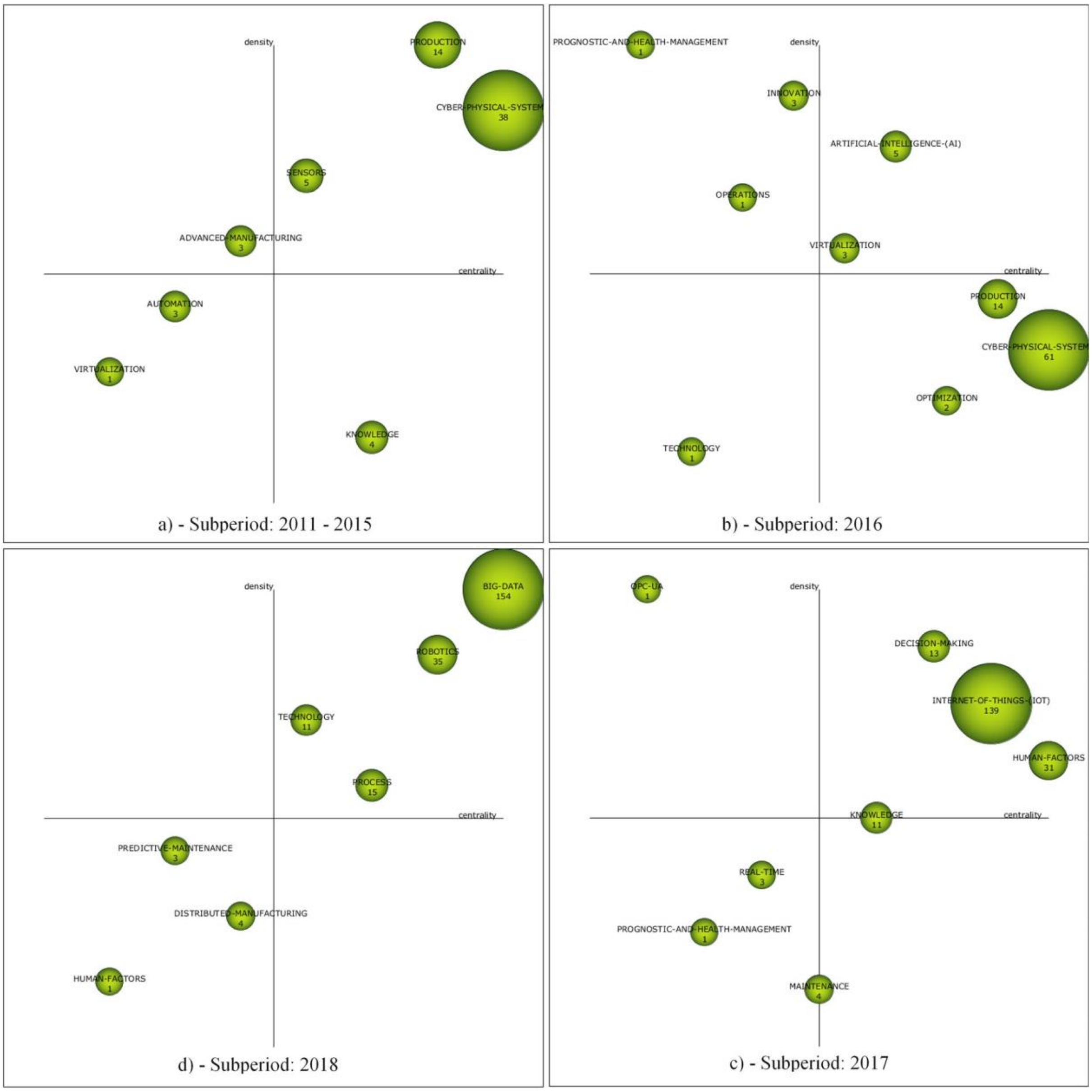

Figure 9. Strategic diagrams (2011–2018). Source: SciMAT.

et al. (2017); Qi and Tao (2018) reported that the big data analytics can be understood as the rapid discovery of hidden and high-value information from a large database, such as trends and patterns and according to Cheng et al. (2018), data mining is the technique used to explore such information.

The 'robotics' presents a dense, central, and important topic with 35 documents and an h-index of 2. The robots have attracted great research attention owing to their ability to replace not only repetitive and unskilled labour but also more complex activities (Freddi 2018). The communication among machines is a key point in industry 4.0, as the robots exchange information about their current situations, allowing dynamic and real-time reconfiguration of the production system (Müller, Grunewald, and Spengler 2018).

The 'technology' and 'process' are the motor themes with medium density and centrality. The 'technology' studies the relation among the contributions of various technologies of the industry 4.0 with regard to the management of operations (Fettermann et al. 2018), technological innovations (Palazzeschi, Bucci, and DI Fabio 2018), professions and labour market (Caravella and Menghini 2018), new knowledge and skills of workers (Freddi 2018), as well as the skills needed by future managers and changes in the educational system (Gitelman and Kozhevnikov 2018). The 'process' indicates the studies related to the process safety and environmental protection, such as those of Junior et al. (2018); Liboni, Liboni, and Cezarino (2018), and Moktadir et al. (2018). We also observe studies related to the digitalisation process of De Felice, Petrillo, and Zomparelli (2018) and process improvements of Tamás (2018), among others.

Analysis of thematic areas

Figure 10 shows the overlapping map of the study field of industry 4.0. The stability index (0.32, 0.32, and 0.23) remained unchanged in a first moment, but it goes down afterwards. Although 1468 (228 343 897) keywords were lost during the four subperiods, the number of keywords increased from 338 (2011–2015) to 1231 (2018). Evidently, the low stability index is a clear sign that the field of research is not mature enough and that it is not completely understood by academics. The high number of new keywords in each subperiod, as well as the increasing from the first to the last subperiod shows that the field of research is evolving and it is attracting the attention from academics that are trying to work and relate new keywords to thefield of research of industry 4.0.

Considering the evolution of the keywords as shown in Figure 10, we now analyse the evolution of the thematic areas in the research field of industry 4.0 (Figure 11). The size of the clusters is proportional to the number of associated documents. The progressive emergence of new keywords confirms the major evolution of the field of industry 4.0. Some clusters such as 'robotics', 'innovation', etc. appear only in a single subperiod. In contrast, the clusters such as 'cyber-physical system', 'human factors', and 'virtualization' are observed in more than one subperiod.

In the first subperiod, there are efforts related to the union of the physical systems with the virtual systems (CPS), sen- sors for capturing and controlling information, automation and virtualisation of processes, impacts on production systems, and the knowledge of workers needed to implement concepts of industry 4.0. In the second subperiod, topics related to artificial intelligence, optimisation of processes and systems, maintenance of machines, and innovation arise. In the third subperiod, the integration between devices and systems (IoT) is highlighted, along with human factors, real-time decision making, and communication platforms (OPC UA). The fourth subperiod is characterised by the great efforts in data analysis and processing (big data), robotisation of processes and collaborative robots, distributed manufacturing, and predictive maintenance.

In the first and second subperiods, the importance of the 'cyber-physical system' is evident. This cluster has a high degree of co-occurrence owing to the sharing of the main themes with 'internet of things' of the third subperiod. A similar scenario is observed for 'big data'. This shows a strong relationship between these terms; Wang et al. (2016) have expressed that these technologies are the pillars of the new industrial revolution.

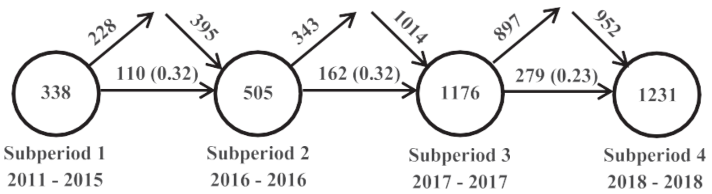

Figure 10. Overlapping map. Source: SciMAT.

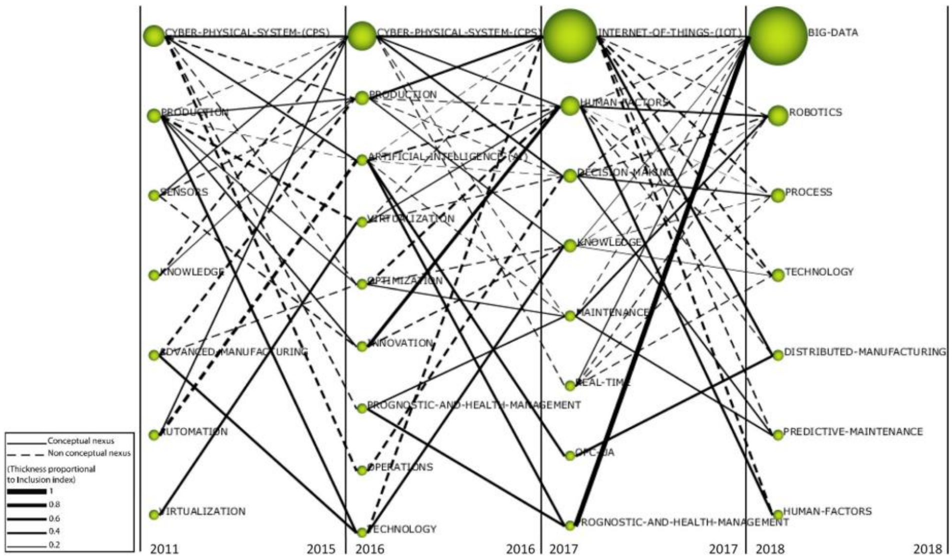

Figure 11. Thematic areas. Source: SciMAT.

While analyzing the cluster 'cyber-physical system', Monostori et al. (2016) and Lee et al. (2018) point out that cyber-physical production system (CPPS) is a fundamental element for the emerging industrial revolution. According to Jakovljevic, Mitrovic, and Pajic (2017), the CPPS represents the maximum level of CPS implementation in the production. However, the defense strategies, known as 'cybersecurity', should be created to avoid potential cyber-attacks in the CPS, which could cause damages such as incorrect production of parts as well as risks to equipment, employees, and consumers (Khalid et al. 2018; Yu et al. 2017).

The same occurs with the cluster 'internet of things'. Zhang et al. (2018) and Cheng et al. (2018) analysed the state of the art and applications of the industrial internet of things (IIoT). Li et al. (2018) point out that the IIoT is superior to the traditional IoT with regard to extensibility,flexibility, centralised management, service quality, real-time emphasis, and reliability. In the same way, the cluster 'big data' presents studies related to the 'industrial big data' that is a term, according to Ji et al. (2016), consisting of processing and analysis of big data, but with high efficiency and ability in dealing with problems faced in the case of the previous methods. The additional feature of the industrial big data is the use of special techniques of data processing that enables identification of hidden patterns and prediction of situations in the production process, and enhancement of efficiency in decision-making (Yan et al. 2017).

The cluster 'production' is observed in thefirst two subperiods. Lean Production is one of the main themes associated with this cluster. Studies by Sanders, Elangeswaran, and Wulfsberg (2016); Wagner, Herrmann, and Thiede (2017); Buer, Strandhagen, and Chan (2018) presented the relationship between LP and I4.0 are increasing in order to evidence the way the concepts interrelate in practice and show that these relationships pointed positive results. The LP has reached its limit, which makes it difficult to meet the requirements of the future market due to the difficulties to enable mass production of highly customised products. and shorter product life cycles, as well as for not using the maximum of modern information and communication technology (ICT), hence the concept of Lean Automation has emerged from the union between I4.0 technologies and LP methods (Kolberg, Knobloch, and Zühlke 2017; Tortorella and Fettermann 2018). Industry 4.0 aims to increase the productivity andflexibility of organisations. These characteristics are evidenced in the principles of LP that, although these concepts present different approaches, have common goals (Buer, Strandhagen, and Chan 2018; Frank 2014).

Furthermore, the relationship between 'PHM' (second subperiod), 'Maintenance' (third subperiod), and 'predictive maintenance' (fourth subperiod) demonstrates a strong investment by academics such as O'donovan et al. (2015); Roy et al. (2016); and Civerchia et al. (2017) in the maintenance area from the use of concepts of industry 4.0.

The 'human factor' can be observed in the third and fourth subperiods. In the third subperiod, this cluster has strong sharing with the terms 'robotics', 'innovation', and 'cyber-physical system'. In this perspective, Scholer and Müller (2017) point out that collaboration between robots and workers can improve process efficiency and increase overall productivity. This industrial revolution is transforming organisations into intelligent factories through the use of advanced analytical information as well as communication and collaboration between people and machines (Lee, Bagheri, and Kao 2015). However, technologies like CPS require workers to be able to deal with the technologies of a high degree of complexity (Wittenberg 2016). On the other hand, such technologies allow workers to utilise the available time productively to create and innovate rather than performing manual activities; therefore, Palazzeschi, Bucci, and DI Fabio (2018) emphasize that innovation is an essential ability of the workers in the era of the fourth industrial revolution. In factories of the future, the advances in technology will not be completely utilised without human intuition and creativity (Gershwin 2018). In this perspective, the industry 4.0 cannot be sustained by technological innovations without the support of the human factor in the form of new skills and competencies of the workers (Dalenogare et al. 2018).

The co-occurrence between the clusters 'technology' and 'knowledge' is analysed by Krzywdzinski (2017), who points out that tacit knowledge and the ability of the workers to interfere in organisational processes can hinder the deployment of new technologies. However, Bauer et al. (2018) stresses that an organisation in industry 4.0 should not restrict itself to the elimination of human resources due to the obsolescence of the manual activities but it should also ensure reallocation of the resources in new business opportunities. According to Womack (1996), improvement projects tend to fail if employees feel that there is threat to their jobs and knowledge and they become redundant for the organisation. Therefore, the workers must contribute to enhance the production process through their innovations, which cannot be provided by the machines.

The relationship of 'decision making' with other clusters such as 'cyber-physical system', 'predictive maintenance', and 'process' is in agreement with studies by Zheng et al. (2018) and Zhong et al. (2013), which state that real-time decision making is a key point of the industry 4.0 through sensors that collect data instantly from the production process. In addition, Zhong et al. (2016) reiterate that technologies such as big data have a strong contribution to decision making on predictive maintenance considering the large data generated by the machines, thus justifying the relationship between the clusters 'big data' and 'predictive maintenance'.

The co-occurrence of robotics and human factors demonstrates the efforts of academics in technologies such as collab- orative robot systems that are emerging with the advent of the new industrial revolution (Weiss, Sharp, and Klinger 2018). These robots are presented as aerial micro-robots (Li and Savkin 2018), robotised manufacturing cells (Brad, Murar, and Brad 2018), 3D printers (Zhu et al. 2018), among others.

The Open Platform Communications Unified Architecture ('OPC UA' in the third subperiod) is the best-known com- munication protocol of the fourth industrial revolution (Cavalieri, Salafia, and Scroppo 2019); this technology allows the introduction of industry 4.0 in companies (García et al. 2018). According to Schleipen et al. (2015); Wang et al. (2017) and Ferrari et al. (2018), this technology enables information exchange and data transfer across the hierarchy of systems that commonly coexist in the industry, delivering interoperable, platform-independent, high-performance, scalable, secure, and reliable communication between applications. In addition, the OPC UA is becoming the standard platform for commu- nication between machines (M2M), thus allowing for self-organisation of the productive process (Ferrari et al. 2018; José Álvares, Oliveira, and Ferreira 2018; Schleipen et al. 2015; Tsuchiya et al. 2018).

The co-occurrence between the clusters 'OPC UA' and 'artificial intelligence (AI)' is in line with the studies by Syam and Sharma (2018), which state that machine learning is a prerequisite for developing artificial intelligence, however, this feature requires a large amount of data (big data) thus justifying the need to use OPC UA technology for communication between machines and sectors.

Distributed manufacturing is a new strategy that aims to decentralise the production of manufactured products (Rauch, Dallasega, and Matt 2017). Thus Rauch, Unterhofer, and Dallasega (2018) indicate that this strategy differs from the tradi- tional one because thefinal product will be assembled or produced close to the customer, thereby increasing the efficiency with respect to the use of resources, improvement in product quality, reduction of production costs, and lower management risk. On the other hand, the communication between the factories will be a great challenge, which can be solved through the use of industry 4.0 technologies (Durão et al. 2017). Hence, it is possible to understand the co-occurrence between the clusters 'distributed manufacturing' and 'OPC UA'

State of the art, main challenges and perspectives of industry 4.0 in international journal of production research

This topic first demonstrates a brief explanation on I4.0 and afterwards an exhaustive research will be presented in the articles published in International Journal of Production Research to develop the state of the art and demonstrate the main challenges and perspectives in I4.0.

Several technological leaps occurred since the beginning of the industrialisation of consumer goods to the current scenario, being recognised as 'industrial revolutions'. The first revolution occurred due to the mechanisation of the industries through the advent of the first hydraulic and steam engines; the second happened due to the intensive use of electric energy and the combustion engine; and the third by the use of information technology and electronics, along with robotics (Lasi et al. 2014); (Drath and Horch 2014). According to Kagermann et al. (2013); Brad, Murar, and Brad (2018) the fourth industrial revolution was expected and recognised as the era of 'Industry 4.0' or 'Smart factories', being a concept that unites technologies for automation and exchange of data, thus allowing the automated control, from the communication between machines, as well as a high degree of efficiency in the use of material and energy resources, making the supply chain more flexible and sustainable. The I4.0 concept wasfirst introduced in Germany in 2011 (Lee et al. 2018) with the aim of raising the level of management and competitiveness of organisations from the convergence between the physical and virtual world (CPS) (Gu et al. 2019). Hence, 'the level of "smartness" of a manufacturing enterprise will be determined by the degree to which the physical enterprise has been reflected in the cyberspace' (Kusiak 2018).

Although Xu, Xu and Duan (2018) point out that the CPS IoT technologies, Cloud Computing are more representative, the I4.0 concept is constituted by the union of several other technologies and concepts such as Big Data (O'donovan et al. 2015; Zhong et al. 2015), Sensors (Lin et al. 2016; Schütze, Helwig, and Schneider 2018), Machine Learning (O'donovan et al. 2018), Simulation (Bonci, Pirani, and Longhi 2016; Meudt et al. 2017; Turner et al. 2016), Additive manufacturing (Dilberoglu et al. 2017; Rauch, Unterhofer, and Dallasega 2018), Artificial Intelligence (Syam and Sharma 2018; Thompson et al. 2018), Augmented Reality (Fernández-Caramés et al. 2018; Masoni et al. 2017; Syberfeldt, Danielsson, and Gustavs- son 2017; Uva et al. 2018), Real Time (Uhlemann et al. 2017; Zhang et al. 2015), Security (Pereira, Barreto, and Amaral 2017; Riel et al. 2017), Robotics (Robla-Gómez et al. 2017; Wahrmann et al. 2019) Information and Communication Tech- nology (ICT) (Haverkort and Zimmermann 2017; Theorin et al. 2017), Virtualisation (Angrish et al. 2017; Lu and Xu 2018), Digital Twin (Haag and Reiner 2018; Zhuang, Liu, and Xiong 2018; Wang and Wang 2018).

From the analysis made from 2011 to August 2018 at the IJPR it was found 26 articles related to I4.0 and thefirst published was in 2016. This state of the art was inspired by studies of Rekiek et al. (2002); Dolgui et al. (2013) and Ivanov et al. (2016). After the exhaustive analysis of the articles, the main perspectives and challenges for I4.0 are presented in Figure 12.

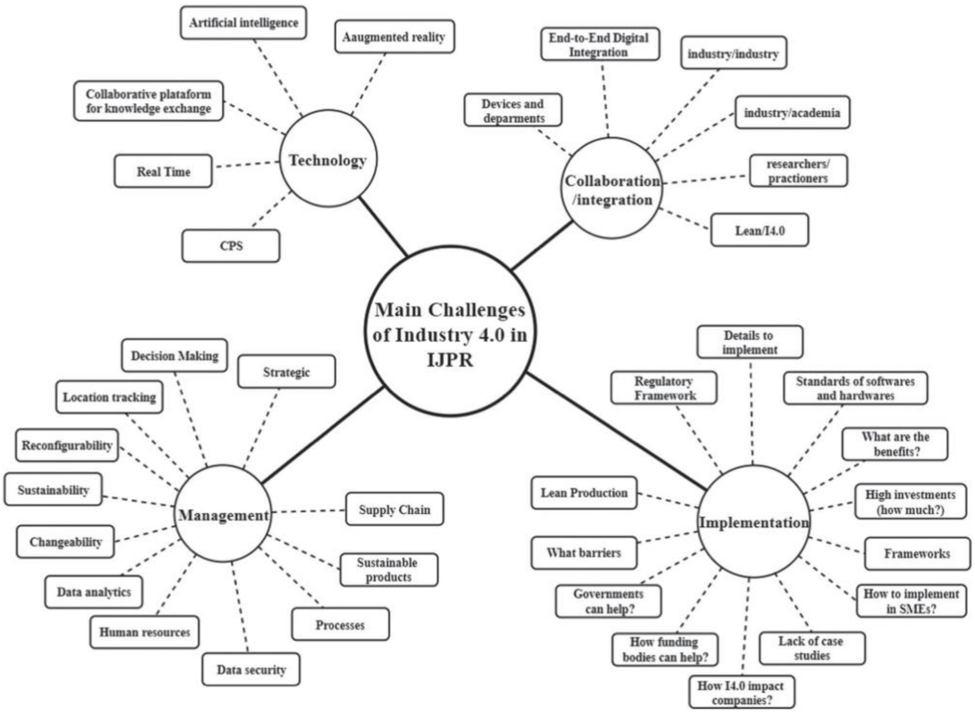

Figure 12. Challenges of I4.0 pointed out in IJPR.

Related articles to industry 4.0 in IJPR

Ivanov, Dolgui, and Sokolov (2019) proposed a dynamic model and an algorithm for short-term supply chain scheduling in order to solve the challenges that the dynamism and evolution of the supply chain in the context of industry 4.0 presents such as differences in machine characteristics (time structure, the speed of operation and processing and dynamic work arrivals). The study contributes with a theoretical formulation of a methodology to solve scheduling problems in environments of industry 4.0. They highlight that the collaborative CPSs are the basis for intelligent factories and that this integration creates challenges and perspectives for new research and work due to the dynamic environment.

Nayak et al. (2016) developed the resource-sharing framework for CPSs with the goal of maximising the utility of CPS through decentralised control. The authors validated the framework from three case studies: scheduling in environments of industry 4.0, energy distribution in smart grids and information routing in multi-robot systems. Also, they listed the main challenges to CPSs modelling: generalised modelling, complexity, characterising CPS behaviour, dynamicity, scalability, resilience, structural/design and security.

Liao et al. (2017) carried out a systematic literature review to analyze the academic articles within the industry 4.0 topic that were published online until the end of June 2016. They point out that engineers working in companies rarely work with academia. This connection is a key challenge to be overcome in order to developing industry 4.0. However, issues such as doubts regarding technology deployment, lack of clarity of benefits, lack of software standards and hardware used to be called the reference architecture model for industry 4.0 (RAMI 4.0), high investment, as well as lack of details about their implementation makes companies present worries concerning the adoption of concepts and technologies. The results also showed the lack of, or insufficient, research efforts, such as the end-to-end digital integration and regulatory framework; and in areas of management such as strategic management, decision-making, location tracking, reconfigurability, and sustainability. The authors also highlight eight priority areas to develop papers and research: standardisation and reference architecture; managing complex systems; delivering a comprehensive broadband infrastructure; safety and security; work organisation and design; training and continuing professional development (CPD); regulatory framework; resource productivity and efficiency.

Through a collaboration between academia and industries, Theorin et al. (2017) developed the Line Information System Architecture (LISA) to perform the integration between services and devices at all levels of the organisation; facilitate hardware modification and new intelligent services; support and promote continuous improvements in data visualisation and management. The software has demonstrated applicability in industries, especially in the automotive sector. The authors point out that organisations are reluctant to implement technologies 4.0 due to the lack of clarity about the benefits that they can obtain, the lack of detail regarding the implementation of such technologies as well as the need for high investments. Another challenge is that many companies already have advanced information systems, but few can simplify integration between devices and industries. Companies alsofind difficulties to manage organisational data in a way of transforming useful knowledge to facilitate and automate decision making.

Zhong et al. (2017) developed and validated a Big Data Analytics for PI-based logistics data which are from an intelligent environment created by deploying RFID readers, tags and wireless communication networks on the production shopfloors. They show that there is a lack of efforts to optimise logistics decision making at intelligent shopfloors.

Hwang et al. (2017) have developed an OEE performance measurement system for industry 4.0 according to the ISA-95 and ISO-22400 standards. The model was implemented from the use of Business Process Modelling and validated through virtual factory simulation. The model enabled real-time performance indicators. They indicated that organisations have difficulties in collecting data in real time with the use of conventional information systems and that the application of the IoT can solve this problem.

Kolberg, Knobloch, and Zühlke (2017) reviewed 41 LP methods and presented an interface that is being developed to unify LP and I4.0 (Lean Automation) concepts by scanning Lean methods using CPS. The authors point out that application of Lean Production has reached its limit, which makes it difficult to meet the requirements of the future market due to the difficulties to enable mass production of highly customised products, and shorter product life cycles, as well as using the maximum of modern technology of information and communication. In addition, they point out that Lean Automa- tion frameworks exist, however, they are proprietary, vendor-dependent solutions and do not support changeability of the production.

Tortorella and Fettermann (2018) applied surveys in 110 Brazilian manufacturing companies to examine the relation- ships between Lean Production practices and technologies of industry 4.0. The results showed that organisations that present a high degree of implementation of technologies 4.0 also present a high level of application of Lean Production methods and that the size of the company does not represent a barrier to the implementation of both concepts. The study also points out that companies that implement Lean Production practices are more likely to adopt technologies 4.0, and their opera- tional performance has positive impacts with the union of concepts. The authors emphasize that there is a need for empirical studies to investigate the relationship between both concepts due to the lack in the literature. In addition, they suggest that Lean Production may be a prerequisite for deploying industry 4.0.

Strozzi et al. (2017) analyzed the scientific evolutionfield of research on 'Smart Factory' and highlighted the research directions for thefield, including the critical areas for development, as well as the trends and emerging topics for future research. The authors point out the need for studies to understand the barriers that affect the implementation of industry 4.0, as well as the way governments and funding bodies can facilitate such implementation. Another point that needs investigation is the organisational impacts as changes in supply chain management, as well as the relationships of the human resources in the development of environments of industry 4.0.

Ben-Daya, Hassini, and Bahroun (2017) investigated the context of IoT and its impact on supply chain management (SCM). They demonstrated the impact of IoT on major supply chain processes: ‘source’, ‘make’, ‘deliver’ and ‘return’. The results show that the efforts of the relations between IoT and SCM are in the ‘make’ and ‘deliver’ areas and that studies in ‘source’ and ‘return’ are deficient. Furthermore, the authors point out gaps as lack of a framework to implement IoT in supply chain contexts; lack of models that address supply chain problems in IoT environments and challenges related to the management of information security, interoperability, maintenance, virtual networkflow design and optimisation, costing, vehicle routing and quality-controlled logistics.

Lee et al. (2018) developed an IoT-based warehouse management system with an advanced data analytical approach using computational intelligence techniques to enable smart logistics for industry 4.0. The data were collected from a case company. The results improved the efficiency of the receiving process; enhance the order fulfil performance; improved order accuracy and efficiency of order picking. The authors suggested future researches using industry 4.0 technologies to improve warehouse efficiency.

Miranda-Ackerman, Azzaro-Pantel, and Aguilar-Lasserre (2017) presented a framework to develop products focused on sustainability in economic, social and environmental terms (S^3: sensing, smart and sustainable). To validate the concept is presented a case study that demonstrated the creation of a CNC machine. They showed that a great challenge for organi- sations is to develop, in addition to the organisational processes, products that are capable of monitoring its functionality, to work in an interconnected environment and to have manufacturing processes aimed at a holistic and sustainable view from the point of view economic, social and environmental.

Putman et al. (2017) proposed a virtual fusion environment that allows a real-time combination of a virtual work part in a physical manufacturing system. The framework was validated through experiments that demonstrated synchrony between physical and virtual. They showed the lack of real-time operating environments with the physical manufacturing system, which leads to the loss of important information and opportunities for improvement.

Moeuf et al. (2018) performed a literature review of current applied research covering different industry 4.0 issues related to small and medium-sized enterprises (SMEs). The results showed that SMEs uses industry 4.0 concepts only for monitoring industrial processes and still lack implementation in issues involving production planning. The study also points out that SMEs are limited to using only technologies like Cloud Computing and the IoT. They suggest case studies to investigate the real benefits of applying the industry 4.0 concepts in SMEs and to identify how other technologies can benefit organisations as well as the impacts on internal processes.

Kusiak (2018) investigated the roots of smart manufacturing, the pillars of smart manufacturing, applications in the most diverse areas, as well as the future of smart manufacturing, its opportunities and challenges. The author points out the need to develop large-scale collaboration between industries with greater social impact to enhance digital transformation by creating collaborative platforms that allow the exchange of knowledge between companies. In addition, the participation of SMEs in these collaborative environments is fundamental.

Yin, Stecke, and Li (2018) presented the evolution of production systems from I2.0 through industry 4.0 focusing on the analysis of relations between product supply and customer demand. The authors suggested the investigation of how industry 4.0 technologies affect current production systems and how the environment of these systems will adapt to the implementation of industry 4.0 concepts and technologies. In addition, rigorous case studies should be applied in order to generate a greater understanding of how to manage the changes generated by industry 4.0 in production systems.

The systematic literature review of Buer, Strandhagen, and Chan (2018) explores the novel between Lean Produc- tion and industry 4.0 and performs the scientific mapping of literature. The authors point out the challenges for future research related to the impacts of industry 4.0 on ‘soft’ lean practices; the facilitating effects of Lean Production on industry 4.0 implementations; empirical studies on the performance implications of an industry 4.0 and Lean Production integra- tion; implementation framework for moving toward industry 4.0 and Lean Production integration. Also, studies on the implications for organisational performance and the environmental factors influencing the industry 4.0 and Lean Production scenario are missing. Another point evidenced was the lack of applicability studies of Lean Production and industry 4.0 integration in non-repetitive production environments.

Moghaddam, Nof and Y (2018) developed a framework that uses cloud manufacturing systems and an algorithm for dynamic integration of manufacturing services and components in a collaborative network of organisations. Experiments are performed to prove the efficiency and benefits. The authors suggested expanding the application of the framework in areas such as hospitals and health care institutions; universities and laboratories; multinational corporations; teams of robots and wireless sensor networks.

Gu et al. (2019) proposed a framework to achieve effective and efficient EPR (Extended producer responsibility) from the manufacturer perspective and integrates information systems and enables life cycle management. The framework was validated in a case study at Haier, a Chinese multinational. The authors point out that industry 4.0 facilitates the implemen- tation of EPR programmes. However, SMEs present challenges to implement industry 4.0 concepts due to the need for high investments. Future research should be conducted in the areas of cyber-security and supply chain management, as well as real industry 4.0 applications.

Ivanov, Dolgui, and Sokolov (2019) investigated the influence of digitalisation and industry 4.0 on the ripple effect in the supply chain risk analytics. To do so, they proposed two frameworks. The authors point out the need to develop research related to analytics algorithms in combination with optimisation and simulation modelling in order to improve the supply chain in the context of industry 4.0. In addition, one must undertake data-driven empirical research, as well as in marketing andfinance and new technologies such as blockchains or omnichannel.

Müller, Grunewald, and Spengler (2018) developed a genetic algorithm for the redundant configuration of robotic assem- bly lines with stochastic failures to maximise the production rate of the line. With a numerical analysis, improvements in productive processes were demonstrated. They pointed out the challenges that need to be overcome as mixed-model case; decision-making regarding the type of robot most appropriate toflexibilise and optimise the production line. There is also a need for control policies to decide which buffers should be reallocated, as well as methods of producing a configuration in a short time.

Brad, Murar, and Brad (2018) proposed a framework that brings valuable tools and means to comprehend and improve remote connectivity, reconfigurability, smartness and changeability in environments of industry 4.0. The authors point out the need to investigate key parameters that characterise changeability and reconfigurability, as well as the way these parame- ters are related. Another challenge is to understand the specifications that explain the objective functions for reconfigurability and changeability.

In the context of the future of manufacturing systems, Gershwin (2018) investigated the technologies and the importance of the role of the intuitive ability of humans in the future of MS. They also presented cases of successful applications of MS engineering research. They recommend the development of MS research teams. This team must be constituted of people with practical knowledge and experience of MS; expertise, experience and knowledge of modern mathematical modelling and analysis, and advanced IT skills. In addition, this group of researchers should work closely with professionals with a practical understanding and knowledge of the shop-floor. The authors point out challenges such as differences in perspectives and culture between researchers and workers with practical experience. Workers with manufacturing knowledge have a local perspective. Since researchers skilled in mathematical modelling and analysis, as well as IT knowledge must consider broader consequences of their local proposals. Another challenge is to understand to what extent human intuition will be necessary and important because of advances in industry 4.0 technologies.

Wang, Ong, and Nee (2018) conducted a survey of the research studies in ubiquitous manufacturing (UM) to understand the technical features, characteristics and a broad range of applications of UM systems published between 1997 and 2017. They point out the need for technologies for data processing in order to support big data analytics; standardisation of UM systems; artificial intelligence to understand the users and augmented reality to improve processes.

Kumar et al. (2018) developed an integrated method for simultaneously determining job sequencing, batch-sizing, inventory levels and preventive maintenance schedule. The method was tested in a complex production environment of an automotive plant, presenting significant economic improvements. After an evaluation study of the method to identify the robustness and the possibility of application in various production scenarios. They suggested studies that integrate the methodology proposed in the areas related to the planning of quality control, process planning and supply management.

Wang and Wang (2018) introduced digital twin and industry 4.0 to the waste electrical and electronic equipment (WEEE) remanufacturing industry in order to provide an integrated and reliable cyberavatar of the individual WEEE, therefore forming personalised service system. The proposed system was validated and assessed through applications in the cloud and CPS. The authors point to the challenge of developing digital twin protection and security methodologies to ensure that CPSs allow only to allow the right workers to have access to information. Other challenges are related to the dissemination and education of the WEEE handling, as well as the development of robust and easy-to-use systems to support the stakeholder engagement with limited knowledge and experience.

Main challenges, perspectives and future research in industry 4.0

Through the exhaustive research carried out on the 26 articles related to industry 4.0 in IJPR, 36 main challenges were found. These challenges were clustered in 4 large groups: Technology, Collaboration/Integration, Management and Implementation (Figure 12).

The 'Implementation' is the cluster that has the greatest number of challenges to be overcome, followed by 'Manage- ment', 'Collaboration/Integration' and 'Technology'. This represents the lack of understanding about the implementation of industry 4.0 in companies. Therefore, researchers need to develop studies to improve the understanding of how industry 4.0 technologies and concepts impact processes, products and services, especially referred to CPS, Real Time, Collaborative platforms, AI and Augmented reality. However, such researchers should conduct work in parallel with organisations in order to join efforts, combining academic theory with practical knowledge. The governments should also be involved in these integrations in order to facilitate and develop ways of cooperation among sectors and to make efforts and investments to develop relations between universities and companies. This university-industry-government relationship develops the 'triple helix' of innovation and entrepreneurship, which are critical for economic growth and social development pointed out by Etzkowitz and Zhou (2017). Therefore, the implementation of industry 4.0 concepts will require conditions of collaboration not only at the global level, but also at the regional level through the strengthening of the triple helix. On the other hand, the lack in this model is evidenced by Veza, Gjeldum, and Mladineo (2015), being the lack of an organisation or institution that promotes the relationship between university-industry-government, and can be solved through the creation of Learning Factorys, which are characterised by the selective simplification or gradual reduction of complex and large-scale production processes and will have as function to carry out the link between the different sectors involved. However, no study of Learning Factorys was found in the IJPR, hence, we suggest future work relating this theme to develop industry 4.0. Companies are still concerned about the implementation of the industry 4.0 concepts due to the high investments, the need for a high-quality workforce, lack of software standards and hardware used to be the reference architecture for the industry 4.0 (RAMI 4.0) and lack of knowledge of the real benefits for companies. Therefore, future research should be carried out in order to develop frameworks for deploying industry 4.0 in real applications, not only in large companies but also in SMEs. On the other hand, teams of researchers must work with professionals with shop-floor knowledge. Kusiak (2018) suggests that to enhance digital transformation is necessary to create collaborative platforms that allow the knowledge exchange between companies.

In addition, Tortorella and Fettermann (2018) have demonstrated that companies that implement Lean Production prac- tices are more likely to adopt technologies 4.0, and their operational performance has positive impacts with the union of the concepts. Other benefits may also be evidenced in studies by Kolberg, Knobloch, and Zühlke (2017); Buer, Strandhagen, and Chan (2018) Kolberg. Therefore, Lean Production can be afirst step to develop industry 4.0, because if a company that does not have a customer-oriented culture that is not focused on waste reduction, applying automation technologies will only intensify poor process inefficiencies structured.

We also suggest future works related to supply chain management, mainly related to the development of algorithms, because Ivanov, Dolgui, and Sokolov (2019) affirm that the 'success in supply chain competition will become more and more dependent on analytical algorithms in combination with optimization and simulation modeling'. The results also showed the lack of studies in management, such as decision making, human resources, sustainability, among others (Figure 12).

We suggest future researches related to human resources, because the transition to a such sophisticated production will not be possible immediately due to the high financial costs as well as the lack of skilled and talented workers. Therefore, industry 4.0 brings challenges in the social sphere, requiring companies to develop their workforce at the highest levels of competence and to attract new talent to handle with the increased complexity inherent in the new industry 4.0 technologies (Bokrantz et al. 2017; Enke et al. 2018; Wittenberg 2016), since this qualified labour force capable of conducting the fourth industrial revolution will already be lacking in the market (Block, Kreimeier, and Kuhlenkötter, 2018), particularly for SMEs companies (Mattsson et al. 2018).

Therefore, future researches will be carried out to develop frameworks and case studies from the integration of concepts and technologies of Lean Production and industry 4.0. Also, future works are being developed linking I4.0 with sustainability, supply chain management, human resources and processes.

Conclusion

The present study shows that the quantum of research activities related to industry 4.0 is doubling each year. We identified expert authors in thisfield, as well as the periodicals that published the most on this subject. The scientific evolution presented 31 clusters whereby the most representative ones were with motor theme: 'CPS', 'IoT', and 'Big Data'. With great efforts by the scientific community, it was possible to identify areas such as the union between lean production and industry 4.0, production-centered CPS (CPPS), IoT (industrial internet of things - IIoT), industrial big data, among others.

The appearance of the clusters CPS in the first and second subperiod, IoT in the third, and Big Data in the fourth demonstrates the efforts of researchers in the main technologies of the industry 4.0, thereby establishing that it is necessaryfirst to unite the physical systems with the virtual ones (CPS) and then to make the connection between devices, systems, products, machines, and people (IoT); this integration will produce a large amount of data (Big Data) that will serve to anticipate and solve problems in advance, increase flexibility and organisational efficiency. On the other hand, studies on the change in the form of work with the advent of industry 4.0 and the way the robotics impacts and collaborates with workers have shown the strong areas of interest for academics. Another important development is observed in thefield of maintenance, which benefits from the use of large amounts of data (Big Data), allowing effective predictive maintenance. The thematic evolution has demonstrated the major themes in thefield of industry 4.0 over the years, as well as their relationships through co-occurrence of keywords. The thematic evolution also showed that technologies like OPC UA and IoT are the bases for distributed manufacturing. In addition, it showed how the CPS helps in decision making due to the emergence of a cluster related to the theme. Another point analysed was the importance of the topics related to knowledge management as well as human factors in the industry 4.0. Through an exhaustive research, it was possible to show the state of the art, the main challenges and perspectives in I4.0. This study is limited to analyzing only the Scopus database. Further works can be developed by analyzing databases such as Web of Science, Science Direct, among others. Another limitation is to understand how citations and h-index of clusters are affected by time of publication. Finally, this study provides insights and perspectives for future research (topic 5.2) on the issues in which researchers, universities, business, associations, politicians, and technology providers need to invest efforts to enable a seamless transition to the real-time large-scale implementation of the fourth industrial revolution.

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5 ARTIGO 2 – An overview of 42 years of lean production: applying bibliometric analysis to investigate strategic themes and scientific evolution structure

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SITUAÇÃO ATUAL: Publicado no Technology Analysis & Strategic Management

ABSTRACT

The aim of this paper is to apply bibliometric network analysis to the Lean Production (LP) field of study in order to investigate the strategic themes and the scientific evolution structure. To perform this research, VOSviewer and SciMAT were used to analyse 4,412 documents from 1977 to 2019. The performance analysis of publications, researchers, journals, universities and countries related to LP were measured quantitatively and qualitatively. 24 themes were presented and classified according to their centrality (importance) and density (development), and the intellectual structure of each theme is presented. Lastly, the scientific evolution structure shows the most important clusters over time. The results show that the most important themes are related to manufacturing processes, industrial management, project management and human aspects. Finally, we provide new perspectives to assist researchers in the detection of research opportunities and literature gaps in the field of LP.

1. Introduction

Lean Production (LP) is an approach to production that aims to eliminate waste in organisational processes, providing products and services at the lowest possible cost with a focus on customer sat- isfaction (Shah and Ward 2007). Also known as the Toyota Production System (TPS), it is characterised by reducing variations in the production process and eliminating non-value activities (Furstenau and Kipper 2018; G. Tortorella and Cauchick-Miguel 2018). LP emerged on the shop floors of Japanese manufacturers (Hines, Holwe, and Rich 2004), however, the concept has spread in several areas, pro- viding improvements in operational performance in services (Piercy and Rich 2009), healthcare (Kipper et al. 2015), supply chain (Borges et al. 2019), smart manufacturing environments (G.L. Tor- torella and Fettermann 2018), among others.

Despite the benefits that LP provides for companies, few non-Japanese organisations have suc- cessfully applied it (Furstenau et al. 2019). Researchers continue to put effort towards developing a better understanding of LP. In order to contribute to a better understanding of the challenges, trends and perspectives in the LP field of research, some studies focused on performing bibliometric analysis on the literature of the area (Gonçales Filho, De Campos, and Assumpçào 2016; Ciano et al. 2019; Taddeo et al. 2019; de Oliveira, Sousa, and de Campos 2019). Although such research is impor- tant, no study is known to have performed a complete analysis of the whole period of scientific pub- lications (1977—2019) of LP. Therefore, in-depth studies of LP must be performed to help researchers in future works and contribute to the continuation of research in this area.

With this goal in mind, this paper aims to provide a complete background of the strategic themes and scientific evolution structure found in the LP literature. To this end, we applied per-formance and bibliometric network analysis on the LP field of research. This approach facilitates understanding by creating a holistic observation of the field, helping to illustrate the develop- ment of, and relationships between, scientific works of several researchers over time. The result- ing strategic map and depiction of the evolution of knowledge will help generate a new comprehension into this field of research, making it possible to provide new perspectives in order to assist the detection of research opportunities, gaps and future decisions (Cobo et al. 2011; López-Robles et al. 2019).

2. Methodology and dataset

For this research, we used the Scopus and Web of Science (WoS) databases. The period was defined from 1977 to 2019. The LP search terms were defined: ‘lean production’ OR ‘lean manufacturing’ OR ‘toyota production system’, which were used by (Buer, Strandhagen, and Chan 2018). Terms including ‘just in time’, ‘six sigma’, and several others (Ciano et al. 2019) were not used because they rep- resent aspects and features of LP. A filter was used to find documents that contain any of the search terms in the title, abstract and keyword. The search was restricted to English language articles. The date of export of the documents was 11 November 2019. The software used was the SciMAT (Science Mapping software Analysis Software Tool) (Cobo et al. 2012) and VOSviewer (van Eck and Waltman 2010). 5930 documents were selected for bibliometric analysis from Scopus (4009) and WoS (1921) databases, which presented a total of 14,766 keywords. In preprocessing, 1,518 duplicate documents were excluded. After this, 1,131 words representing the same concept were grouped, such as ‘just in time’ and ‘JIT’, ‘value stream mapping’ and ‘VSM’, among others. At this stage, terms such as ‘lean production’ and ‘toyota production system’ were excluded because we wanted to identify unfami- liar words. Moreover, misspelled words have been corrected, as well as irrelevant words such as ‘article’ have been removed.

A total of 4,412 documents and 13,635 words were included for analysis. The analysed items were keywords and the extraction of relevant information was the frequency of co-occurrence of the key- words, - i.e. the number of documents in which the words appear together. To calculate similarity, the equivalence index was used, which calculates the bond strength between the clusters represen- tative of each theme. The clustering algorithm used to detect themes was the simple centre algor- ithm, which demonstrates the clusters’ binding force. The themes obtained through the clusters were plotted in two-dimensional diagrams that have four quadrants, based on density (y-axis) and centrality (x-axis) values. Density measures the strength of the relationship between each keyword within a theme. The density provides a good representation of the capacity of the theme to sustain and develop over time in the field of research. It is defined as d —— 100 (Ze¡j/), where i and j are keywords belonging to the theme and w is the number of keywords in the theme. Centrality measures the strength of how a cluster relates with other clusters (Cobo et al. 2011). It is defined as c —— 10 " Zekh. where k is a keyword belonging to the theme and h is a keyword belonging to other theme. The centrality means that a cluster is a necessary point of passage and critical for any interested researcher to invest efforts into understanding (Cobo et al. 2011).

Research themes were classified into four groups as shown in Figure 1(a),: (a) /Horor themes: high centrality and density (important themes for the field of research with high development); (b) BaSIC and Transversal Themes: High centrality and low development (tend to become motor themes in the future due to their high centrality); (c) Emerging or Declining Themes: low centrality and density (need for qualitative analysis to define whether it is emerging or declining); (d) Highly Developed and Iso- lated Themes: low centrality and high development (no longer important due to a new concept or technology) (Cobo et al. 2012).

The thematic network structure Figure 1(b), assist to understand how the strategic themes co-occur with other subthemes related to the field of research. This co-occurrence and the develop- ment of such relationship defines if a cluster is important in terms of centrality and density (Cobo et al. 2012).

The thematic evolution over time was explored to discover the evolution of the research themes, period of time, origins, and interrelationships. To this end, the thematic evolution map was created with the inclusion index. Figure 1(c), illustrates a classic map. The solid line (lines 1 and 2) indicates that the connected clusters (A' and A2, B' and B2) share the main theme (name of main theme e the- matic nexuses), the dashed line (line 3) characterises that the clusters (B' and C') share elements that are not the main themes (name of main theme e thematic nexuses), and the absence of a line means discontinuity (D! and D2 being a new cluster). The thickness of the lines is proportional to the inclusion index, and the volume of the spheres is proportional to the number of published docu- ments associated with each cluster (Cobo et al. 2012).

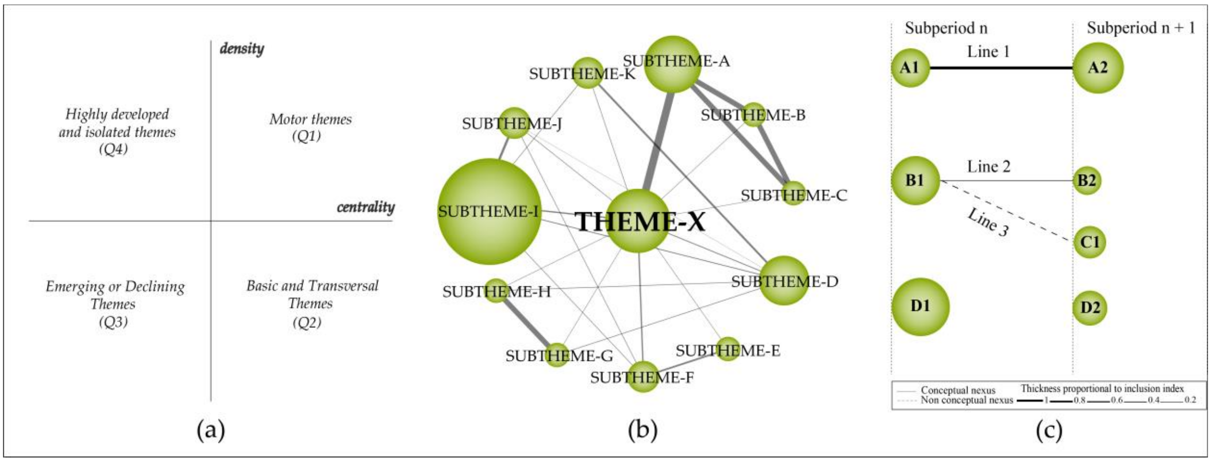

Figure 1. Strategic Diagram (a). Thematic Network Structure (b). Thematic Evolution Structure (c). Source: Cobo et al. (2012).

The development of the science mapping of this research takes place over the period: (1977—2019). The strategic diagram reflects the whole period and the thematic evolution was divided into four subperiods respectively: 1977—1987; 1988—1998; 1999—2009 and 2010—2019.

For the performance analysis we used SciMAT and the VOSviewer software. VOSviewer support the creation of a two-dimensional map to analyse the relationships between publications, research- ers, countries, universities in order to identify the most productive and cited ones to help research decision-making (van Eck and Waltman 2010).

3.Performance bibliometric analysis of LP

In this section, the performance analysis of publications, researchers, journals, universities and countries related to LP from 1977 to 2019 were measured and each resulting theme was interpreted.

3.1. Publications over time

Regarding the number of publications over time (1977—2019), the number of documents analysed in each subperiod is, respectively: 5, 295, 1,436, and 2,676; totalling 4,412 documents analysed using SciMAT. It is possible to observe in Figure 2 the appearance of the first paper that related LP concepts and methods in 1977 (Sugimori et al. 1977). The first study performed using the concept of LP was 'Triumph of the Lean Production System' (Krafcik 1988) published in 1988 (Holweg 2007). Only in 1990 did the field of research start to gain popularity, due to the publication of 'The Machine that Changed the World' (Womack, Jones, and Roos 1990). This publication became influential in spreading the LP concept likely because it presented accessible language to practitioners, and the coincidence of its publication with the major crisis of the U.S. auto industry (Holweg 2007). The rising of publications follows until 2012, and starts to fall until 2014, but the field of research pre- sented a considerable recovery in 2015.

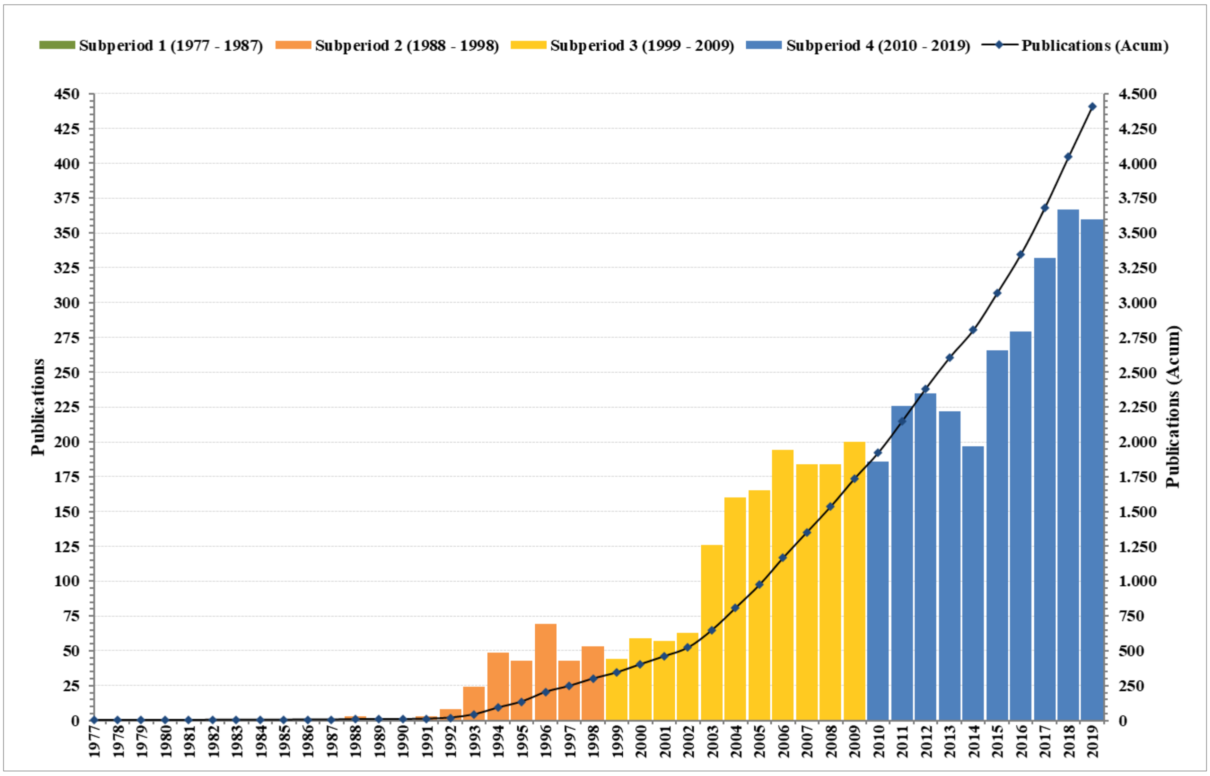

Figure 2. Number of publications from 1977 to 2019. Source: SciMAT.

3.2. Performance Analysis of Authors, Journals, Universities and Countries

Figure 3 (below) shows the network of authors who have at least 3 publications related to LP. It is possible to observe 18 coloured clusters being the most developed and strengthened while the grey clusters are still in the process of maturation and isolated. The distance between the clusters represents the relatedness of the researchers in terms of co-authorship links and the closer the location of the researchers, the stronger their relatedness (van Eck and Waltman 2013).

As shown in Table 1, it is possible to observe that Tortorella, G.L. is the most productive researcher in the field of LP, following by Vinodh, D. and Kodali, R.. However, the most cited researcher is Shah, R., followed by Ward, P.T. Their main contribution is concentrated in 2 documents: ‘Lean Manufac- turing: Context, Practice Bundles, and Performance’ (Shah and Ward 2002) and ‘Defining and Devel- oping Measures of Lean Production’ (Shah and Ward 2007). Also, the researchers that appear in both sides are Towil, D.R., Vinodh, S. and Kodali, R.

Although the number of publication and citations are one of the most important metrics for per- formance analysis, the capacity of a researcher to develop research collaboration networks must be highlighted. The research collaboration networks is a researcher’s capability to connect works (co- authoring publications) and projects (joint grantsmanship) between researchers in achieving research goals (Huang 2014).

Figure 4 presents the key researchers networks and the overlay visualisation which measure the most recent publications (active authors) in the field of LP (van Eck and Waltman 2013). ' T'*h’ e latest publications are concentrated in the Tortorella’s network (Cauchick-Miguel, P.A., Fettermann, D., among others), however the network from Li, Z., Khalili, A. and Gellynck, X. also must be highlighted due to the higher number of recent publications.

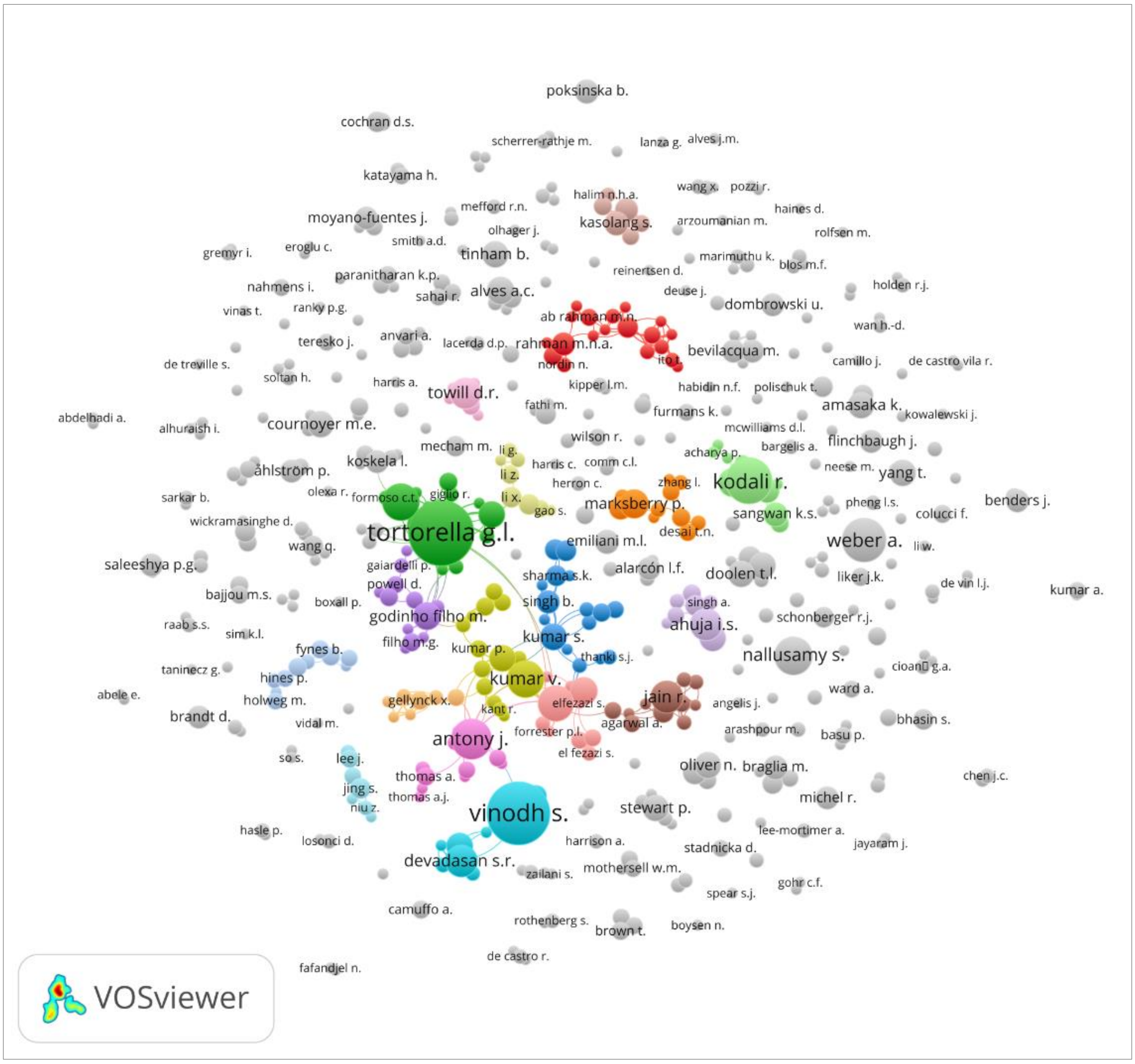

Figure 3. Co-authorship network analysis of LP (at least 3 documents).

Table 2 shows the journals that publish the most in LP (at least 25 documents): International Journal of Production Research (IJPR), followed by Journal of Manufacturing

Technology Management (JMTM) and International Journal of Operations and Production Management (IJOPM).

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Table 1. Most cited/productive authors from 1977 to 2019. Source: SciMAT.

Most cited authors	**Doc.**	**Cit.**	**Most productive authors**	**Doc.**	**Total link strength**
Shah, R.	3	2367	Tortorella, G.L.	42	62
Ward, P.T.	2	2307	Vinodh, S.	39	27
Towill, D.R.	17	2006	Kodali, R.	24	21
Christopher, M.	6	1247	Weber, A.	22	0
Sarkis, J.	3	1231	Antony, J	22	17
Zhu, Q.	2	1219	Nallusamy, S.	18	9
Rich, N.	4	1115	Garza-Reyes, J.A.	18	25
Vinodh, S.	39	1111	Ahuja, I.S.	18	14
Kodali, R.	24	981	Towill, D.R.	17	9
Holweg, M.	5	978	Saurin, T.A.	17	20
Hines, P.	5	963	Kumar, V.	17	24

Figure 4 (below) presents the key researchers networks and the overlay visualization which measure the most recent publications (active authors) in the field of LP (van Eck and Waltman 2013). The latest publications are concentrated in the Tortorella’s network (Cauchick-Miguel, P.A., Fettermann, D., among others), however the network from Li, Z., Khalili, A. and Gellynck, X. also must be highlighted due to the higher number of recent publications

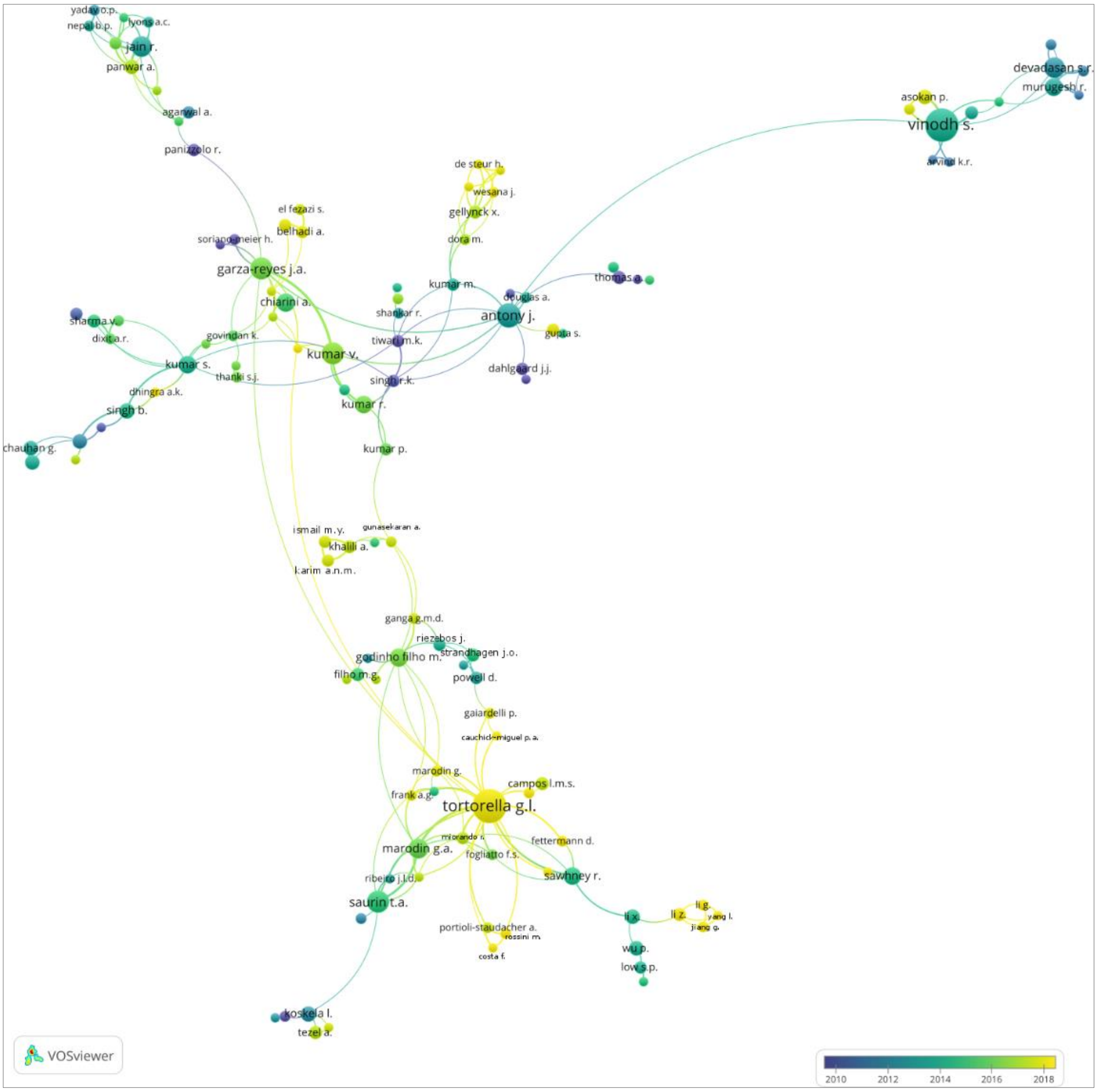

Figure 4. Most important co-authorship network of LP researchers (at least 3 documents).

Table 2 (below) shows the journals that publish the most in LP (at least 25 documents): International Journal of Production Research (IJPR), followed by Journal of Manufacturing Technology Management (JMTM) and International Journal of Operations and Production Management (IJOPM).

Table 2. Most journals of LP from 1977 to 2019. Source: SciMAT.

Journals	Doc.	Cit.	Total link strength
International Journal of Production Research	158	6161	1132
Journal of Manufacturing Technology Management	102	3461	1092
International Journal of Operations and Production Management	92	5589	943
International Journal of Lean Six Sigma	86	1781	631
Production Planning and Control	73	2094	682
Assembly	69	12	1
Manufacturing Engineering	66	98	0

International Journal of Production Economics	48	3925	513
International Journal of Advanced Manufacturing Technology	47	1190	382
Journal of Cleaner Production	44	1883	293
International Journal of Productivity and Performance Management	41	1170	311
International Journal of Productivity and Quality Management	38	343	179

Figure 5 (below) shows the impact factor of journals according to citations of LP documents among journals. The IJPR presents the higher number of publications and the IJOPM, followed by International Journal of Production Economics (IJPE) and Journal of Cleaner Production (JCP) presents the higher impact factor.

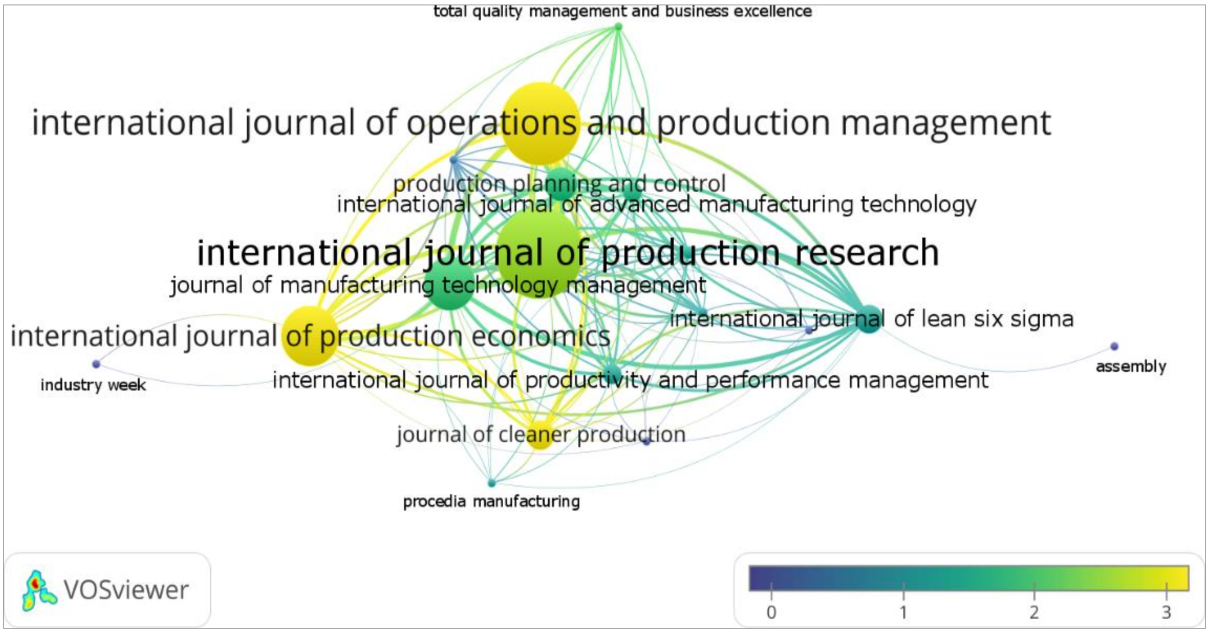

Figure 5: Citations of documents among journals (at least 25 documents).

Regarding the countries (Table 3, below), the USA (944) is first in publications, followed by India (438) and United Kingdom (387). Although the USA concentrate the higher number of publications, Brazil presents to be the most productive recent papers, followed by India, China, Malaysia and Russian federation as shown in Figure 6 (below). The universities that publish the most are the Federal University of Santa Catarina (61) is first in publications, followed by the Cardiff University (56) and the Federal University of Rio Grande do Sul (50).

Table 3. Most productive countries from 1977 to 2019 (Source: SciMAT).

Country	**Doc.**	**Cit.**	**Total link strength**
United States (USA)	944	28,662	7195
India	438	6406	4643
United Kingdom (UK)	387	17,139	4935
Brazil	173	2383	2757
Malaysia	146	1492	1645
Italy	133	2464	1711

Germany	128	1176	420
Sweden	113	3812	1366
Australia	105	2688	996
China	105	2072	499
Canada	90	2287	813
Spain	87	2377	1275
Japan	72	1951	357
Taiwan	67	1027	394
Netherlands	65	1673	712
Iran	63	735	31
France	51	758	34
Portugal	50	622	14
Russian Federation	45	114	4
Norway	36	608	20
Poland	35	200	12

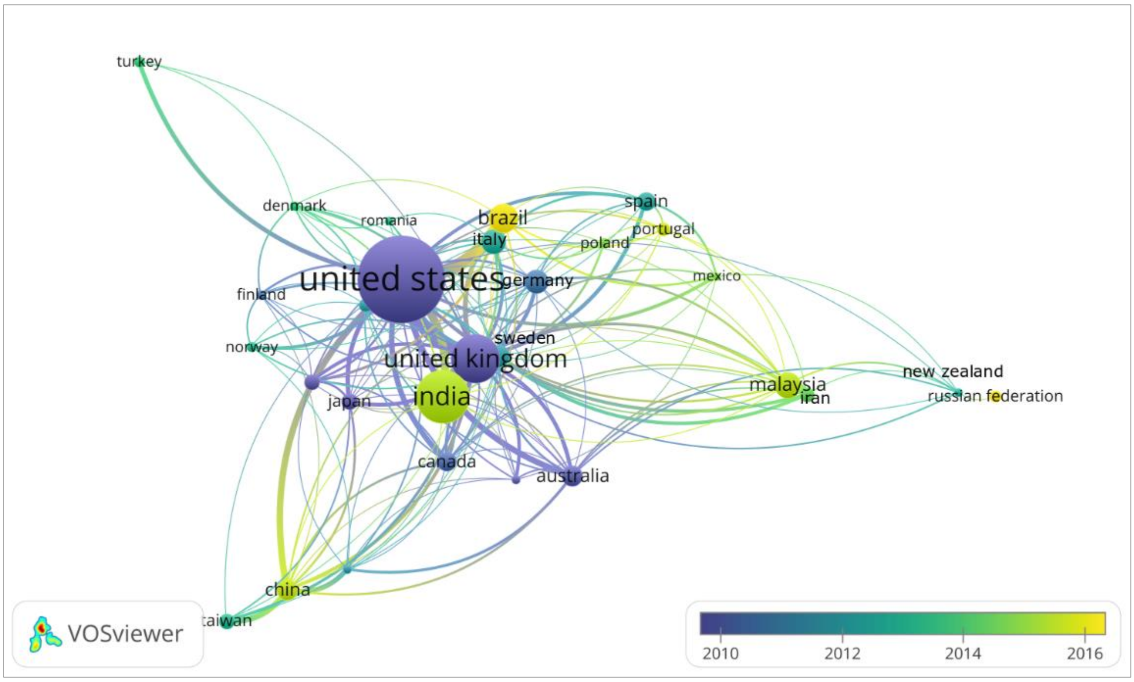

Figure 6. Citations of documents among journals (at least 25 documents).

4. Strategic Diagram and Intellectual Network Structure of LP from 1977 to 2019

In Section 4, the strategic themes of LP are presented. Figure 7 (below) shows 24 clusters classified according to its density and centrality. The number of core documents (documents that appear in at least two nodes) and sum of citations "(number of citations)" appears inside the clusters. Appendix A and B contains diagrams depicting the intellectual network structure of each cluster and its relationship with sub-themes. Table 4 (below) presents the performance analysis of each research themes from 1977 to 2019.

Table 4. Performance of the research themes from 1977 to 2019 (Source: SciMAT). Quadrant 1: Motor Themes. Quadrant 2: Basic and Transversal Themes. Quadrant 3: Emerging or Declining Themes. Quadrant 4: Highly Developed and Isolated Themes.

Themes	Core documents	h-index	Sum citation	Quadrant
MANUFACTURE	446	52	11,050	1
INDUSTRIAL-MANAGEMENT	334	41	10,066	1
HUMAN	145	37	4,909	1
QUALITY-CONTROL	215	35	5,258	1
WORK-SIMPLIFICATION	186	34	4,137	1
PROJECT-MANAGEMENT	180	33	4,156	1
SUPPLY-CHAIN	101	30	3,734	2
COMPUTER-SIMULATION	100	25	2,787	1
ASSEMBLY	124	22	1,58	1
DECISION-MAKING	53	21	1,293	2
REVIEW	46	19	2,205	1
HUMAN-RESOURCE-MANAGEMENT	78	16	1,014	4
LEAD-TIME	37	16	596	3
WASTE-MANAGEMENT	56	14	1,083	1
SUSTAINABILITY	32	14	661	3
PRODUCTION	33	13	601	3
BENCHMARKING	40	12	717	4
MANUFACTURING-PROCESS	34	10	733	2
LEAN-THINKING	21	10	770	3
5S	25	9	229	4
OPERATIONS-MANAGEMENT	15	8	846	3
INFORMATION-TECHNOLOGY	32	7	387	3
BARRIERS	5	4	363	3
SUPPLIERS	5	3	44	3

4.1 Motor Themes of LP

Figure 7 (below) presents 10 clusters classified as motor themes. The most important motor theme is “MANUFACTURE”, due its centrality. This cluster shows the importance of LP for the manufacturing sector. Appendix A (c) shows the interrelationship with main sub-themes such as: “AGILE-MANUFACTURE-SISTEMS”, “VALUE-STREAM-MAPPING” and “SUSTAINABLE-DEVELOPMENT”. This intellectual network highlights the struggle of the academy to develop studies relating to LP and agile manufacturing systems, perhaps because reducing waste and meeting customer demand seems to be not enough. Organizations must respond quickly to market changes accelerating product and service development, as well as strategic alliances development. In this context, efforts seem to be focused on the development of hybrid lean–agile manufacturing systems. Besides, the relationship of the cluster “MANUFACTURE” with other main sub-themes demonstrates researchers’ efforts in the development of lean methodologies within the manufacturing sector, mainly regarding to the application of the Value Stream Mapping (VSM). VSM is one of the first LP techniques to be adopted by professionals in order to map the value flow and identify losses in production processes. The loss reduction approach itself is very relevant in terms of sustainable development. In this context, LP along with green manufacturing paradigms, enable continuous improvement for waste minimization.

The second most important theme is “INDUSTRIAL-MANAGEMENT”, as shown in Figure 7 (below). The most important sub-themes are “COMPETITION and “CUSTOMER-SATISFACTION” (Appendix A (b)). This theme is notable due to studies that discuss how organizational management practices are being influenced by lean philosophy, emphasizing that cultural changes are necessary for its implementation. Another important sub-theme is “PRODUCTION-ENGINEERING”. This concept originated from industrial engineering. Its practices are related to cost-reducing strategies, which are crucial in building the narrative of competitiveness and consumer satisfaction. Production engineering complement LP through methods with support of time study, motion study, process management, among others. Therefore, the production engineering seems to be the most important field of study that is related and focused in the LP field of research.

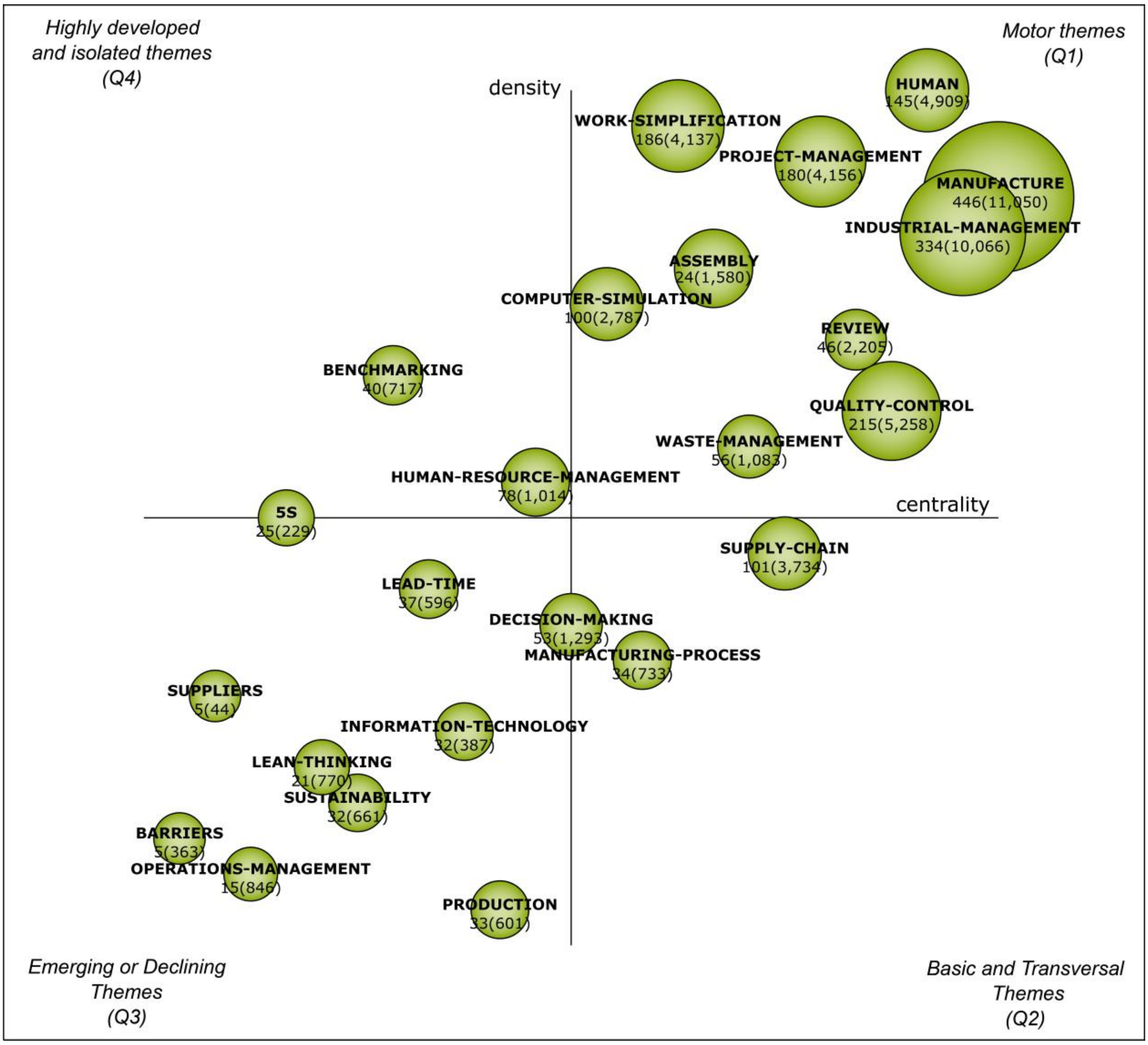

Figure 7. Strategic diagram from 1977 to 2019. Source: SciMAT.

The most developed cluster in terms of density is “HUMAN” (Figure 7, above), which is related to human capability development to set standards and sustain results across the organizations. The term ‘human’ presents several meanings in the LP field of research. Still, the concept of human resource management (HRM) seems to be a major related topic . Appendix A (a) shows the relationship with one of the most relevant sub-themes, “TOTAL-QUALITY-MANAGEMENT” (TQM). The TQM concept has in its core the development of leadership and involvement of workers with lean principles. This social aspect is an essential issue when implementing TQM in companies, therefore the HRM strategy must be wisely designed to shape employees' quality-oriented attitudes. The success of LP in companies has not been completely based on application of suitable techniques and tools alone, but also built on the human aspects. The theme ‘human’ is also influenced by the sub-theme “HEALTHCARE”. The LP initiatives in healthcare provides a perspective where the patients are seen as customers, driven by a need for organization efficiency, in measures such as patient lead times, costs due to wastes, and quality improvement, by using VSM in healthcare and other LP techniques. Several studies are related to HRM in healthcare in order to understand not only the role of leadership for LP implementation, but also the development of skills of healthcare professionals to participate in the LP initiatives.

The cluster "PROJECT-MANAGEMENT" (Appendix A (d)) has a relationship with sub-themes such as "PRODUCTION-CONTROL", "COST", "LEAN-CONSTRUCTION", "CONSTRUCTION-INDUSTRY", and they appear as the most important in its network. The theme is heavily influenced by the themes of lean thinking applied to construction, with a focus on the introduction of waste management tools in project delivery practices. Studies seek to understand not only the concepts of loss reduction in construction but also to measure the performance of project deliveries, in order to prove the efficiency of LP in reducing costs in construction.

The cluster "WORK-SIMPLIFICATION" (Appendix A (e)) has a relationship to sub-themes including "SIX-SIGMA", "PROCESS-ENGINEERING", "LEAN-SIX-SIGMA", "QUALITY-IMPROVEMENT" and "SMALL-AND-MEDIUM-ENTERPRISES". This theme has a strong influence on Six-Sigma practices integrated with LP. Publications reinforce reduction of operational costs related to the quality of production through process improvement practices, focused on the implementation of Lean Six-Sigma (LSS), especially in small and medium-sized companies (SME). Some publications also emphasize the importance of senior management's commitment to the implementation of the methodologies. Recent studies demonstrate efforts to integrate LSS approach with sustainability performance through waste management and quality improvement initiatives. The relationship between quality and process improvement seems to be the central focus of the studies, which among other topics, also address measures for waste management related to quality performance.

The cluster "ASSEMBLY" (Appendix A (f)), and sub-themes such as "AUTOMOTIVE-INDUSTRY", "SCHEDULING" and "AUTOMOBILE-MANUFACTURE", appear as the most important in its network. The theme is affected by the application of lean techniques in assembly lines of different segments, but especially in automobile manufacturing. Publications are focused on improvements in the assembly process, with the application of lean techniques for identification of losses and material reducing in process. The lean techniques are used to improve assembly routines, in situations such as revision of standards, in order to bring more clarity to the assembly procedures to the workforce and for the re-evaluation of workplaces for non-value activities and gaps in security reduction (Finnsgård et al. 2011).

Clusters such as “COMPUTER-SIMULATION” and “WASTE-MANAGEMENT” also must be highlighted. In this context, simulation models have been applied to represent the "before" and "after" scenarios in order to demonstrate to managers the potential benefits of LP and how it can be used to improve waste management. The simulation-based training can also be used to teach lean concepts and techniques to the new workforce by visual learning (Burch V and Smith 2019).

4.2 Basic and Transversal Themes of Lean Production

There are 3 basic and transversal themes, as shown in Figure 7. The most central cluster is “SUPPLY-CHAIN”. The number of core documents associated with this cluster shows the efforts of academics to apply LP techniques in a holistic perspective such as supply chains. Its relationship with the sub-theme “SUPPLY-CHAIN-MANAGEMENT” highlight the attempt to develop LP in supply chain management (G.L. Tortorella, Miorando, and Marodin 2017). The cluster “MANUFACTURING-PROCESS” is the second most important, but less developed and its relationship with the sub-theme “DISCRETE-EVENT-SIMULATION” (Appendix B (o)) presents studies aiming to unite simulation technology with lean practices in manufacturing processes. The third cluster “DECISION-MAKING” (Appendix B (n)) shows how the implementation of LP can provide necessary information for decision-making in companies, especially using VSM in union with multi-criteria analysis (Ramesh and Kodali 2012). The lean information is a new line of lean concepts and its application is used to reduce waste in information and improve the communication flow.

4.3 Emerging or Declining Themes of Lean Production

In order to identify if a cluster is emerging or declining, a qualitative analysis must be performed. Figure 7 (above) shows 8 clusters. The cluster “INFORMATION-TECHNOLOGY” must be highlighted due to researchers’ efforts to understand the relationship of IT technologies with LP practices, known as Lean Automation (Kolberg, Knobloch, and Zühlke 2017). The relationship with sub-themes “RFID”, “INTERNET”, “COMPUTER-INTEGRATED-MANUFACTURING” and “SOFTWARE ENGINEERING” (Appendix B (p)) demonstrates those efforts. This cluster seems to be emerging due to the fact that LP has reached its limit (Hines, Holwe, and Rich 2004), and struggles to provide a mass production of highly customised products, shorter product life cycles, as well as for not using the maximum of I4.0 technologies such as big data, internet of things, cloud computing, among others (Kipper et al. 2019). The union of LP and I4.0 might help in one of the biggest challenges of LP, which is its implementation, since evidence points out that companies are more likely to implement LP when present levels of I4.0 technologies are high. The contrary is also true (G.L. Tortorella and Fettermann 2018).

The cluster “BARRIERS” (Appendix B (w)) also seems to be emerging due to efforts to understand the main difficulties and barriers to implementing LP in companies. The sub-theme “IMPLEMENTATION” highlights that issue, pointing to studies that help to identify and remove such barriers (Zhang, Narkhede, and Chaple 2017). These barriers are represented by a total of 24 topics, and the most relevant are financial constraints, lack of commitment, support and leadership of top management, as well as cultural differences and workers resistance. It is possible to observe that there are several sectors in industry facing barriers in implementation due to organizational culture matters, so the discussions regarding the commitment of the leadership and workers are constant, from food processing to healthcare sectors.

The cluster “SUSTAINABILITY” (Appendix B (r)) presents the researchers’ pursuit to achieve a more sustainable production by using LP Techniques (Vinodh, Arvind, and Somanaathan 2011), such as Sustainable VSM (Cherrafi et al. 2016). Although the cluster is still emerging, the sub-themes “GREEN-MANUFACTURING” and “EMPLOYEE-INVOLVEMENT” highlights the research’s efforts to develop the social and environmental aspects of the Triple Bottom Line.

The cluster “LEAN-THINKING” Appendix B (t)) and its relationship with the sub-themes “LEAN-TRANSFORMATION” and “CHANGE-MANAGEMENT” show the efforts to encourage studies related to the strategic thinking of LP (Lean Thinking) in order to improve the supply chain dimension, and the need to change of manager’s mindset in order to be aligned with the lean thinking to support the lean transformation in companies (Hines, Holwe, and Rich 2004).

4.4 Highly Developed and Isolated Themes

The cluster “BENCHMARKING” (Appendix B (m)) and its relationship with “KPI”, “BEST-PRACTICES”, PERFORMANCE and “MANUFACTURING-STRATEGY”, shows researchers’ efforts to evaluate, compare and assess the application of LP in companies, its advantages and disadvantages, and how LP can affect working conditions. In this sense, although the benefits of LP, on the other hand, the philosophy also has been criticized (Hines, Holwe, and Rich 2004), and studies show the negative conditions of its application due over work (known as “karoshi” in Japan caused by cardiovascular and cerebrovascular disease) (Nishiyama and Johnson 1997), pressure on employees to avoid mistakes, higher production responsibility, intolerance with team members and work stress (Jackson and Mullarkey 2000). This might occur due to the misapplication or misunderstanding of LP, which can cause contrary effects in operational performance (G.L. Tortorella and Fettermann 2018). In this context, the appearance of the cluster “HUMAN-RESOURCE-MANAGEMENT” and its relationship with the sub-themes “ORGANIZATIONAL-LEARNING”, “HUMAN-ENGINEERING”, “KNOWLEDGE-MANAGEMENT” and “TEAM-WORK” can be justified. In this sense, LP is not a “set of mechanistic hard tools and techniques and the human dimensions of motivation, empowerment and respect for people are key elements to the long-term sustainability of any lean programme, regardless of the industry sector” (Hines, Holwe, and Rich 2004).

5. Scientific Evolution Structure of LP from 1977 to 2019

Figure 8 (below) shows the overlapping map and the evolution structure. In the first subperiod (1977 – 1987) 11 keywords were used by authors in 5 documents and the most significant are: “PERSONNEL” and “AUTOMOBILE-MANUFACTURE”. These clusters represents the beginning of LP in literature, the first highlights the start of researcher’s efforts to understand the TPS basic concepts which are not only higher value added products and waste management, but also the respect for personnel aspects which is related to the possibility of professionals to use they full potential and develop capabilities by active involvement in order to improve their own work station. The second cluster shows the need to comprehend the applications of TPS concepts in different automobile manufacture companies such as General Motors. Other studies were performed in order to understand how LP originated and how the Japanese manufacturing methods could provide benefits for companies.

In second subperiod (1988 – 1998), 799 new keywords were used, 4 (36%) from the first subperiod (1977 – 1987) were utilized again and 7 were lost. In this subperiod 295 articles were published in scientific literature. The cluster “MANUFACTURE” proves the manufacturing sector owns the most attention of LP and despite the concept spread from the automobile industry to computer industry, construction projects (lean construction), among others. However, “AUTOMOBILE-MANUFACTURE” remains as one of the most important themes due to researcher's efforts to understand how LP spread from Toyota to not only for others car's big companies such as General Motors, Mercedes-Benz, Volvo, Volkswagen, Renault, Mitsubishi and Skoda but also for automotive suppliers. After the "machine" book, LP spread around the world, hence the cluster "STRATEGIC-PLANNING" appears as the most important theme in the second subperiod highlighting the need for a better understanding of LP pillars and methods such as: Heijunka, JIT, Kanban, Poka-Yoke, Kaizen, TQM, among others. These concepts were a key factor to top management and decision makers to incorporate LP in companies strategic planning and, consequently, improve operational performance. In the second subperiod clusters related to LP such as "TOTAL-QUALITY-MANAGEMENT", "PRODUCTION-ENGINNEERING" and "OPTIMIZATION" began to get momentum.

From the second subperiod to the third subperiod (shown in Figure 8, above) 385 (48%) keywords were repeated and 4390 new keywords were used, totalizing 4775. Besides, 1436 articles were published in the scientific literature. This subperiod is represented by 11 clusters. The cluster "INDUSTRIAL-MANAGEMENT" is the most important in the development of LP research field at the time and highlights the importance of LP to industry sector related not only to strategic planning but also customer satisfaction, inventory control, competitiveness, cost effectiveness, marketing, sales and industrial economics. These subjects are closely related to production engineering, which explain its strong co-occurrence with industrial management. The second most important cluster is "PRODUCTION-CONTROL", the lean production control was running in parallel with quality control in terms of research efforts and was applied in order to reach manufacturing stability and pull systems (JIT) not only for mass production, but also for high-variety and low-volume manufacturing environments. In order to improve and assist lean production control, researches were developed highlighting the impacts and benefits of integration of LP practices with computer simulation, information technology, ERP, among others automation technologies. In this sense, the cluster "AUTOMATION" emerges since process require a rigorous communication among separate areas of the organization and many companies realized LP practices were a key factor to implement and improve automated manufacturing processes (Orr 1997). In this sense, researchers pointed out LP must precede automation through a holistic integration of technology with the social-technical system, since this strategy was applied by Japanese companies, which offered competitive advantage when compared with American and European firms. The clusters "MANUFACTURE" and "AUTOMOTIVE-INDUSTRY" remain in the third subperiod but more expressive in terms of publications.

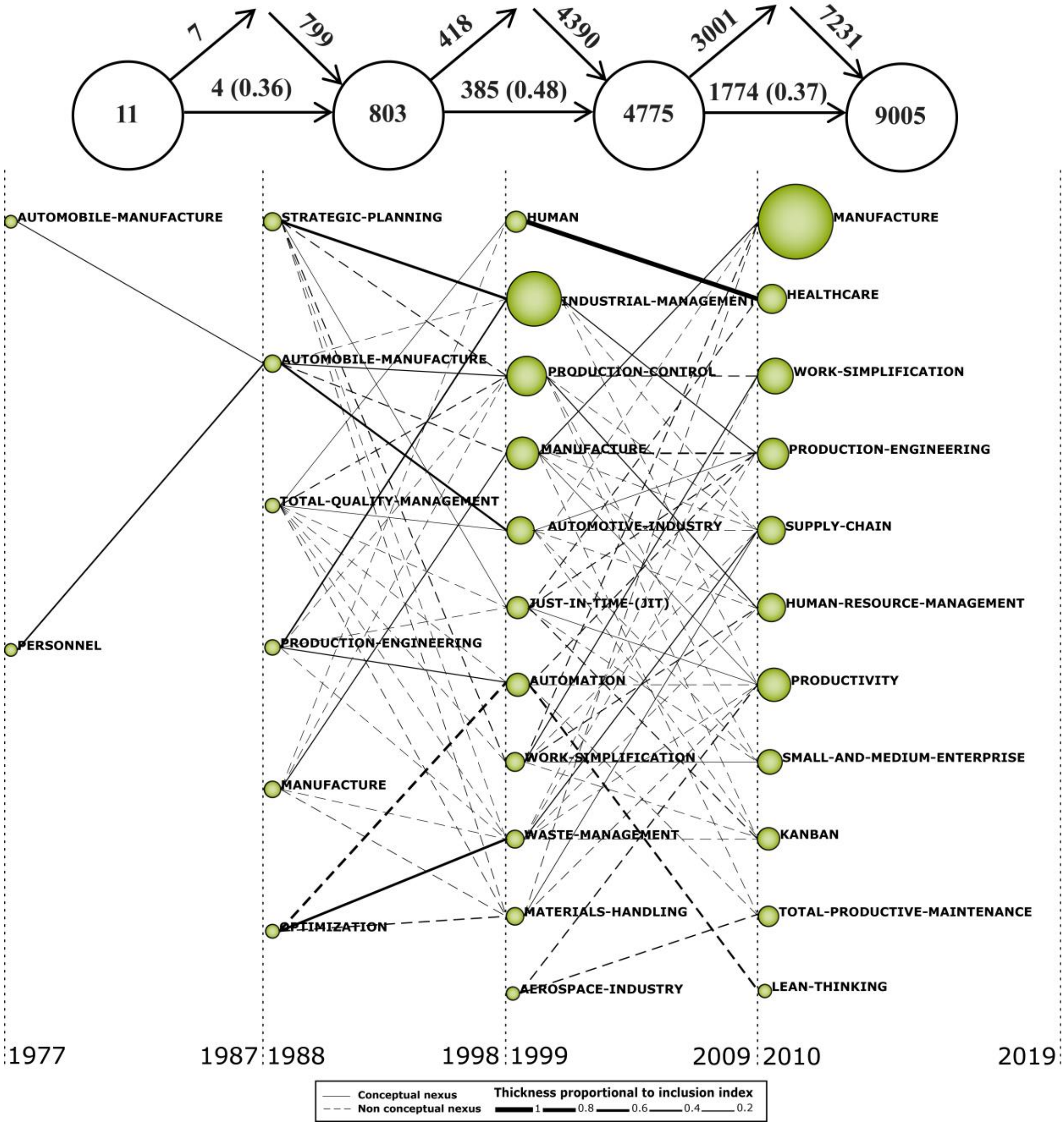

Figure 8. Overlapping Map and Scientific Evolution Structure of LP from 1977 to 2019. Source: SciMAT.

From the third subperiod (1999 – 2009) to the fourth subperiod (2010 – 2019) (shown in Figure 8, above) 1774 (37%) keywords were repeated and 7231 new keywords were used, totalizing 9005. Besides, 2676 articles were published in the scientific literature. As expected, in the fourth subperiod (2011 – 2019) the cluster “MANUFACTURE” carries on as the most important theme and studies related to VSM, agile manufacturing and sustainable development are the most explored by LP’s researchers. The cluster “WORK-SIMPLIFICATION” is the second most explored, to simplify work researcher’s focus in studies related to process engineering and LSS. Although, Womack and Jones helped a lot of Europeans and North American companies to implement LP in the 90's, they stressed companies to incorporate in its strategic planning a new model called as "lean enterprise", which represents a group of lean companies focused in the entire value chain in order to avoid value stream desynchronization, because isolated lean initiatives become impossible to an organization maintain momentum and reap the full benefits of LP (Womack and Jones 1996). In this sense, the rise of the cluster "SUPPLY-CHAIN" can be justified since it seems to have a need to develop the lean supply chain management. The clusters "HEALTHCARE" and "SMALL-AND-MEDIUM-ENTERPRISE" highlights the dissemination of LP into the healthcare systems and SME. The same phenomenon is occurring with "HUMAN-RESOURCE-MANAGEMENT" in order to understand how HRM is related to LP practices can impact in operational performance not only of large companies, but also in SME.

6. Conclusion

A research field can weaken due to the lack of development on the subject as occurred in 2014, as shown in Figure 2 (above). Thus, it is the responsibility of companies, universities, governments, practitioners and academics to join efforts in order to avoid this phenomenon, since the fact that resistances in the implementation of LP in companies become more complex due to the lack of leadership, training, financial resources, among others. Therefore, we encourage the development of the research collaboration networks and the dissemination of the LP to other disciplines such as administration, and other engineering courses, since LP is investigated mainly by production engineering. Our findings also shows that the researcher's efforts are focused not only in lean practices and tools, but also in human aspects, since the misunderstanding of LP can cause bad effects in operational performance. On the other hand, we still suggest more studies in the field of HRM, since this cluster presented be highly developed and isolated. We also suggest future works related to the union of I4.0 and LP, since our findings highlights positive results by this integration. Related topics address computer simulation, which help to demonstrate real benefits of LP to managers and training the new workforce to better understand lean concepts and tools.

The objective of this paper was to apply a bibliometric performance and a network analysis in the field of study of LP in order to investigate the strategic themes and scientific evolution structure. Our findings presented the number of publications over time, the most important publications, productive and cited researchers, as well as the universities, countries and journals related to LP research. Also, 24 major clusters were presented and classified according to its centrality and density, which the most developed and important are related to manufacturing processes, industrial management, project management and human aspects. The scientific evolution structure presented the most important cluster over time. The limitations of this study also must be highlighted. We only discussed main sub-themes related the central clusters. The analysis was limited to articles and reviews in English, and only two databases, WoS and Scopus, were used. To conclude, future studies should be conducted to investigate each cluster in more depth in order to identify challenges, perspectives and new visions of the LP field of research. Besides, emerging themes such as sustainability, lean thinking, industry 4.0, barriers, among others, must be developed in order to support researchers and practitioners in LP implementation. Also, studies are going to be performed in order to explore the evolution structure of LP overtime as well as its tools, techniques, challenges and barriers.

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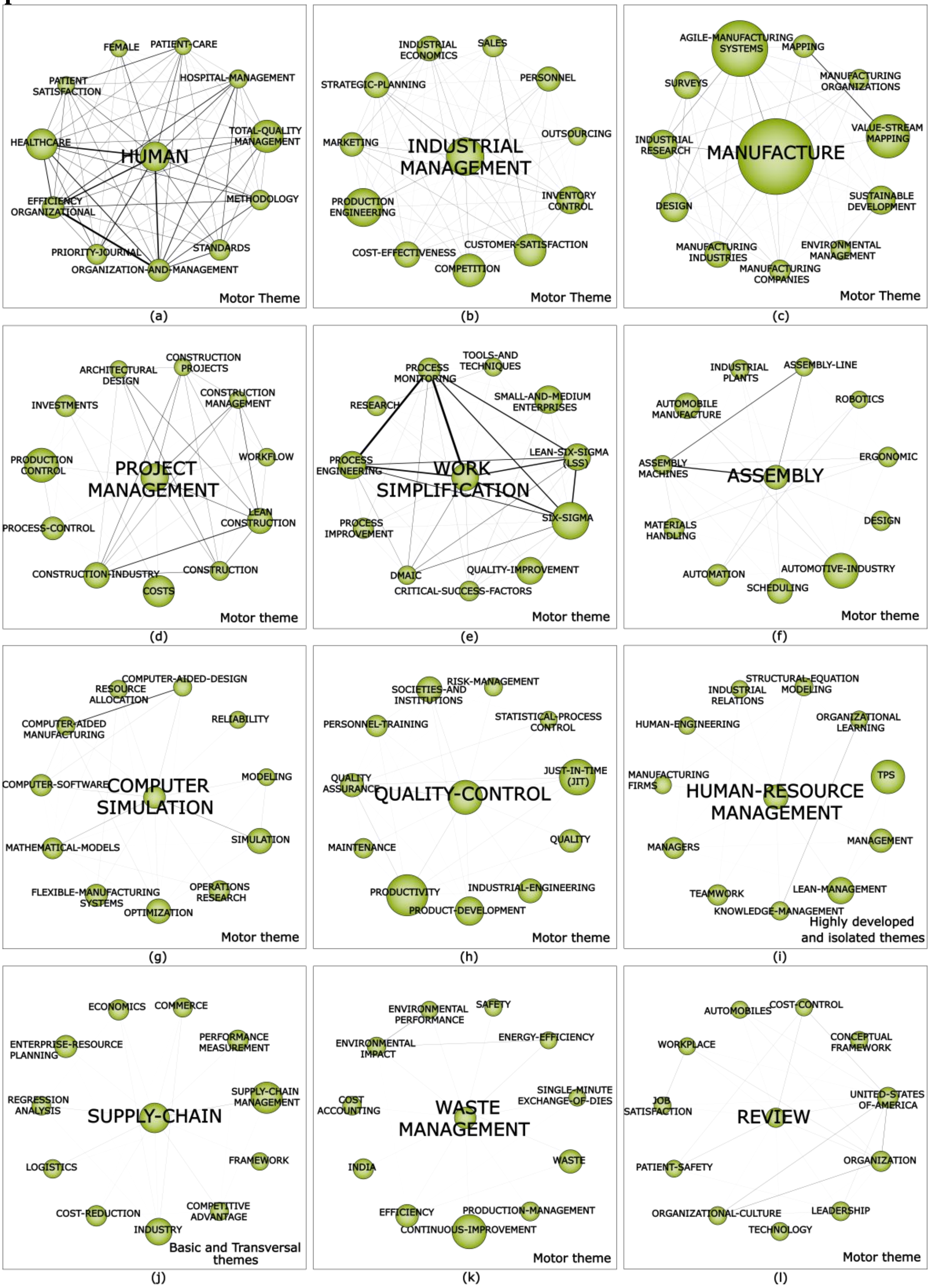
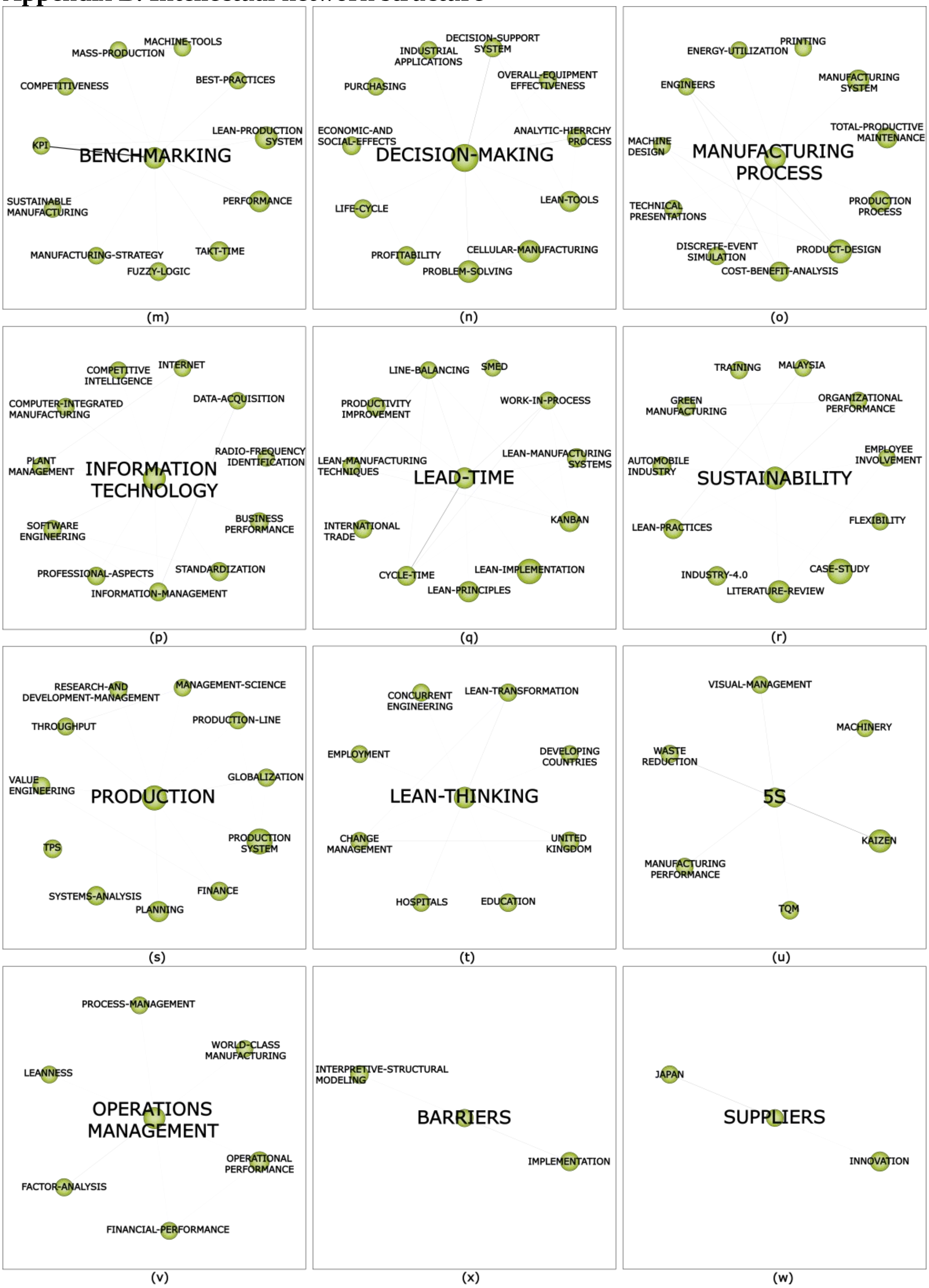
Appendix A. Intellectual network structure



Appendix B. Intellectual network structure



6 Discussão dos resultados: contribuições teóricas e práticas para trabalhos futuros

Esta dissertação teve como objetivo mapear o campo de pesquisa da I4.0 e LP e identificar as relações entre ambos os conceitos, bem como desenvolver possíveis caminhos de pesquisa e aplicação na área da saúde. O primeiro artigo objetivou em analisar a evolução do campo de estudo da I4.0 ao longo do tempo e os principais temas estratégicos, bem como os principais desafios e perspectivas das tecnologias emergentes. Os resultados deste estudo podem ser utilizados por tomadores de decisão em esferas universitárias, empresariais e governamentais, já que a implementação da I4.0 nas empresas continua sendo um desafio. Portanto, os pesquisadores precisam desenvolver estudos para melhorar a compreensão de como as tecnologias e conceitos da I4.0 impactam processos, produtos e serviços, especialmente no que se refere a CPS, Tempo Real, Plataformas colaborativas, IA e Realidade aumentada. No entanto, estes trabalhos precisam ser desenvolvidos em paralelo com as organizações, a fim de unir esforços, combinando a teoria acadêmica com o conhecimento prático. Os governos também devem estar envolvidos nessas integrações, a fim de facilitar e desenvolver formas de cooperação entre os setores e de realizar esforços e investimentos para desenvolver as relações entre universidades e empresas. Essa relação universidade-indústria-governo desenvolve a "triple hélice" de inovação e empreendedorismo, que são essenciais para o crescimento econômico e o desenvolvimento social apontados por Etzkowitz e Zhou (2017). Portanto, a implementação dos conceitos da I4.0 exigirá condições de colaboração não apenas em nível global, mas também em nível regional por meio do fortalecimento da triple hélice. Por outro lado, a carência desse modelo é evidenciada por Veza, Gjeldum e Mladineo (2015), sendo a falta de uma organização ou instituição que promova a relação universidade-indústria-governo, podendo ser sanada por meio da criação das “learning factories”, ou fábricas de aprendizagem, as quais são bastante utilizadas em países desenvolvidos como Alemanha, que se caracterizam por utilizar conceitos de LP e pela simplificação seletiva ou redução gradual de processos produtivos complexos e em grande escala e terão como função realizar a ligação entre os diversos setores envolvidos.

Os principais desafios evidenciados no primeiro artigo estão fortemente relacionados com a união entre I4.0 e PE. Nesta perspectiva, o segundo artigo foi desenvolvido com o intuito de analisar 42 anos de evolução científica do LP e compreender de uma forma mais ampla o campo de estudo. Os resultados mostram que o temas estratégicos estão bastante relacionados com o desenvolvimento da capacidade humana para definir padrões e sustentar resultados em todas as organizações. O cluster “IT” demonstra as relações entre tecnologias emergentes com técnicas e conceitos LP. Isto se dá ao fato de que LP atingiu seu limite (HINES, HOLWE e RICH 2004) e se esforça para fornecer uma produção em massa de produtos altamente customizados, ciclos de vida de produto mais curtos, bem como para não usar o máximo de tecnologias I4.0 como big data, internet das coisas, computação em nuvem, entre outros (KIPPER et al. 2019). A união do LP e I4.0 pode ajudar em um dos maiores desafios do LP, que é sua implementação, já que as evidências apontam que as empresas são mais propensas a implementar LP quando os níveis atuais de tecnologias I4.0 são alto. O contrário também é verdade (TORTORELLA e FETTERMANN 2018). Além disso, fica evidente a predominância da utilização do LP em sistemas de manufatura, no entanto, diferentes setores estão se beneficiando dos conceitos do LP, estar de ainda apresentarem imaturidade quando comparado com o setor de manufatura. Outro ponto a ser analisado foi a estrutura da evolução científica, a qual demonstra as iniciativas de LP na área de saúde fornecem uma perspectiva onde os pacientes são vistos como clientes, impulsionados pela necessidade de eficiência da organização, em medidas como prazos de entrega do paciente, custos devido a desperdícios e melhoria da qualidade, usando análise do fluxo de valor na área de saúde e outras técnicas de LP. Vários estudos estão relacionados à recursos humanos na área da saúde, a fim de compreender não apenas o papel da liderança para a implementação do LP, mas também o desenvolvimento de habilidades dos profissionais de saúde para participar das iniciativas do LP.

Ambos os trabalhos proporcionaram à esta dissertação uma visão mais ampla dos conceitos de I4.0 e LP. Além disso, a identificação do trabalho de Tortorella e Fettermann (2018), os quais identificaram as relações de LP e I4.0 em empresas de manufatura brasileiras, evidenciando o impacto na performance operacional, proporcionou motivação para seguir pesquisas similares nos sistemas de saúde, já que o tema demonstra uma tendência no segundo artigo e o termo de LH ainda foi pouco desenvolvido pela literatura. Desta forma, trabalhos futuros serão desenvolvidos a fim de identificar as relações das tecnologias 4.0 com as técnicas LP em sistemas de saúde e o impacto desta relação na performance operacional. Espera-se que estes resultados possam servir de base para auxiliar em tomada de decisão e compreender melhor as barreiras e dificuldades em implementar ambos os conceitos em organizações de saúde.

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