UNIVERSIDADE FEDERAL DE SÃO CARLOS

CENTRO DE ENGENHARIA DE PRODUÇÃO

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO DO CAMPUS-SOROCABA

Marina Hernandes de Paula e Silva

**MODELO DE MATURIDADE LEAN-CIRCULAR PARA AUTOAVALIAÇÃO EM EMPRESAS**

Sorocaba

2023

UNIVERSIDADE FEDERAL DE SÃO CARLOS

CENTRO DE ENGENHARIA DE PRODUÇÃO

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO DO CAMPUS-SOROCABA

Marina Hernandes de Paula e Silva

**MODELO DE MATURIDADE LEAN-CIRCULAR PARA AUTOAVALIAÇÃO EM EMPRESAS**

Dissertação apresentada ao Programa de Pós-Graduação em Engenharia de Produção do Campus-Sorocaba para obtenção do título de Mestre em Engenharia de Produção.

Orientação: Prof. Dr. Diogo Aparecido Lopes Silva

Financiamento: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)

Sorocaba

2023

Hernandes de Paula e Silva, Marina

Modelo de maturidade Lean-Circular para autoavaliação em empresas / Marina Hernandes de Paula e Silva -- 2023.
89f.

Dissertação (Mestrado) - Universidade Federal de São Carlos, campus Sorocaba, Sorocaba
Orientador (a): Prof. Dr. Diogo Aparecido Lopes Silva
Banca Examinadora: Prof. Dr. Antonio Carlos de Francisco, Prof. Dr. Rosley Anholon
Bibliografia

1. Lean Manufacturing. 2. Economia Circular. 3. Modelo de Maturidade. I. Hernandes de Paula e Silva, Marina. II. Título.

Ficha catalográfica desenvolvida pela Secretaria Geral de Informática (SIn)

DADOS FORNECIDOS PELO AUTOR

Bibliotecário responsável: Maria Aparecida de Lourdes Mariano - CRB/8 6979

**UNIVERSIDADE FEDERAL DE SÃO CARLOS**

Centro de Ciências em Gestão e Tecnologia
Programa de Pós-Graduação em Engenharia de Produção

## Folha de Aprovação

Defesa de Dissertação de Mestrado da candidata Marina Hernandes de Paula e Silva, realizada em 17/03/2023.

### Comissão Julgadora:

Prof. Dr. Diogo Aparecido Lopes Silva (UFSCar)

Prof. Dr. Rosley Anholon (UNICAMP)

Prof. Dr. Antonio Carlos de Francisco (UTFPR)

O Relatório de Defesa assinado pelos membros da Comissão Julgadora encontra-se arquivado junto ao Programa de Pós-Graduação em Engenharia de Produção.

Dedico esta dissertação a minha família que sempre me apoiou para que eu chegasse até aqui.

**AGRADECIMENTO**

Ao meu orientador Prof. Dr. Diogo A. Lopes Silva pelos ensinamentos, direção durante a pesquisa e incentivo para realização de um trabalho cada vez melhor.

Aos meus pais por terem me proporcionado toda educação que tive até aqui e por me tornarem um ser humano cada dia melhor.

A minha irmã, meus padrinhos e tios que sempre acompanharam meu desenvolvimento e torceram por mim.

Aos meus professores e colegas pelos ensinamentos e parcerias.

Aos meus amigos pela amizade, estímulo e desabafos.

E a minha esposa por estar ao meu lado em cada etapa desse momento tão importante.

Quando você quer alguma coisa, todo o universo conspira para que você realize seu desejo
(Paulo Coelho)

# RESUMO

Eficiência econômica e ambiental são diretrizes cada vez mais comuns na gestão das empresas atualmente. Neste sentido, o *Lean Manufacturing* (LM) integrado aos conceitos do *Green/Sustainable Manufacturing* têm se mostrado eficaz por trazer redução de custos, de desperdícios e impactos ambientais, e aumentar a eficiência no uso de recursos, além de contribuir para aumentar a produtividade, a qualidade e valor ao cliente final. Contudo, ainda falta uma visão holística em tal integração, olhando para todo o ciclo de vida dos processos, produtos e/ou da organização como um todo. Assim, a integração do LM com a Economia Circular (EC) pode trazer esta visão, porém, são poucos estudos que tratam deste assunto. Implementar estes dois conceitos integrados e tornar processos, produtos e ciclo de vida das empresas mais enxutos e circulares, exige uma clara visão dos passos as serem tomados. Modelos de Maturidade são relevantes, pois podem auxiliar as empresas a entenderem onde estão e o que precisam fazer para avançar para os próximos níveis. Sendo assim, o objetivo deste trabalho é desenvolver um modelo de maturidade para a autoavaliação de empresas em relação a implementação do LM e EC em seus processos, produtos e ciclo de vida. O desenvolvimento foi realizado com base nos passos do *design science research*, criando o Modelo de Maturidade Lean-Circular (LCMM). Após o desenvolvimento foi realizada a validação do LCMM com 13 especialistas e a aplicação em 09 empresas brasileiras dos setores da economia primário (1 da região sudeste, 1 do centro-oeste e 1 do norte), secundário (4 da região sudeste e 1 do centro-oeste) e terciário (1 da região sul). Os resultados da aplicação do LCMM mostraram que algumas empresas estão buscando por alternativas mais limpas e sustentáveis antes de entender e mapear o próprio processo e fluxo de valor (ocorrido em até 66% das empresas), podendo assim causar erros no planejamento e na hierarquização/priorização das ações de melhoria. Além disso, a falta de treinamento e conscientização de todos os funcionários em relação ao uso eficiente de recursos esteve presente em 61% das empresas avaliadas. Também se destaca a falta de iniciativas relacionadas ao gerenciamento da eficiência no uso de recursos no ciclo de vida dos produtos, sendo esta uma das principais oportunidades observadas. Assim, o modelo de autoavaliação LCMM pode ser considerado de fácil aplicação e rápido autodiagnóstico, e que o setor secundário (indústrias de manufatura) pode ser o mais beneficiado com a sua utilização. Como conclusão final, o modelo desenvolvido contribui para a literatura sobre modelos de maturidade por combinar as teorias de LM e EC com as perspectivas de processo, produto e ciclo de vida, sendo possível replicar o passo-a-passo proposto para outras áreas de estudo. Como limitação, o estudo não aborda sobre o aspecto social, sendo possível essa abordagem em estudos futuros.


Palavras-chave: produção enxuta, berço-ao-berço, sustentabilidade, nível de maturidade, circularidade.

## ABSTRACT

Economic and environmental efficiency are necessary guidelines in the production management of companies today. Lean Manufacturing (LM) integrated with the concepts of Green/Sustainable Manufacturing has been shown effective in reducing costs, waste, and environmental impacts, increasing efficiency in the use of resources, in addition to contributing to improve productivity, quality and added value to customers. However, there is still a lack of a holistic views on such integration, looking at the entire life cycle of processes, products and/or the organizational level. The integration of LM with Circular Economy (CE) can bring this view into practice, however, there are few studies that address this issue so far. Implementing LM with CE and making companies' processes, products, and the life cycle leaner and more circular, requires a clear vision of the practical aspects to be taken. Maturity Models are relevant in that way as they can help companies understand where they are and what they need to do to advance to the next levels. Therefore, this paper aims to develop a maturity model for the self-assessment of companies regarding the implementation of LM and CE in their processes, products and in life cycle perspective as well. The development was carried out based on the steps of design science research, creating a Lean-Circular Maturity Model (LCMM). After the development phase, the LCMM was validated with 13 experts and applied in practice to 09 Brazilian companies in the primary economy sectors (1 in the Southeast region, 1 in the Midwest, and 1 in the North), secondary (4 in the Southeast region and 1 in the center-west) and tertiary (1 from the south region). The results of the LCMM application showed that some companies are looking for cleaner and more sustainable alternatives before understanding and mapping their value stream (occurred in up to 66% of the companies), thus being able to cause errors in the planning and hierarchization/prioritization of actions of improvement. In addition, the lack of training and awareness of all employees regarding the efficient use of resources was present in 61% of the evaluated companies. Also is highlighted the lack of initiatives related to the management of efficient use of resources in the life cycle of products, which is one of the main opportunities observed. Also highlighted is the lack of initiatives related to the management of efficient use of resources in the life cycle of products, which is one of the main opportunities observed. Thus, the LCMM self-assessment model can be easy to apply, provides fast self-diagnosis, and the secondary sector (manufacturing industries) can be the most benefited from its use. As conclusion, the developed model contributes to the literature on maturity models by combining LM and CE theories with the process, product and lifecycle perspectives, making it possible to replicate the proposed step-by-step for other areas of study. As a limitation, the study does not address the social aspect, this approach being possible in future studies.

Keywords: lean production, cradle-to-cradle, sustainability, maturity level, circularity.

# Sumário

# 1. INRODUCTION

This chapter presents in section 1.1 the contextualization and justification of the research, in section 1.2 the research objectives and in section 1.3 the description of the structure of this dissertation, and it is important to emphasize that the structure of this dissertation follows the format of ‘article collection’.

## 1.1 CONTEXTUALIZATION AND JUSTIFICATION

Given the current exponential growth of the population and the expansion of the consumer class, the report of the World Economic Forum (2022) pointed out the high costs for society if the goal of carbon neutrality is not achieved by 2050. Currently, organizations are under pressure from their stakeholders to incorporate, more and better, new socio-environmental metrics and practices to reduce their negative impacts on the environment (FÓRUM ECONÔMICO MUNDIAL, 2022). For this, guides and management structures are needed to help organizations in this task, toward a more sustainable production.

Before the advent of sustainable production, after World War II, the development of the principles of Lean Manufacturing (LM) began within the Toyota company, a Japanese company in the automotive sector, and in 1960 its essential principles had been defined (WOMACK; JONES; ROOS, 2004). However, it was only in the early 1980s that this production philosophy received greater attention from American and European industries (OHNO, 1997).

The main objective of LM is to deliver more value to the consumer by reducing or eliminating waste. Being waste, the activity that does not add value to the product or the service in the customer's view (WOMACK; JONES, 1997). Activities that do not add value and are considered waste can be divided into eight categories : overproduction, waiting, transport, overprocessing, inventory, moving, defects, and insufficient use of human talent. In addition, LM has five principles: value, value stream mapping, pull flow, and continuous improvement (OHNO, 1997)

LM has a positive relationship with increased production efficiency (WICKRAMASINGHE; WICKRAMASINGHE, 2017), being adopted in several sectors, such as the metallurgical industry (LEME et al., 2018), agriculture (BARTH; MELIN, 2018; RIBEIRO et al., 2022), manufacturing in general (RAMOS et al., 2018), healthcare (MORALES-CONTRERAS et al., 2020), logistics (ZEKHNINI et al., 2021) and civil construction (DE OLIVEIRA REZENDE et al., 2022).

While the need to increase financial gains in a lean way contributed to the rise of LM in the world (WOMACK; JONES; ROOS, 2004), the need to reduce the consumption of natural resources and increase the environmental performance of organizations, culminated in the increase of discussions about the relationship between LM and environmental sustainability to obtain more sustainable operations in companies (SCHMITT et al., 2021). In this context, in recent decades, studies have emerged showing the connection between the LM principles of reducing waste and greater value added, added to the environmental perspective of reducing potential impacts on the environment and the more efficient use of resources (water, energy, materials, chemicals, etc.) (DIESTE et al., 2019).

Most of the literature presents positive points of the integration of LM and environmental sustainability, as it brings economic benefits, with the reduction of financial costs, and environmental, with the reduction of negative impacts on the environment (CALDERA; DESHA; DAWES, 2017; DIESTE et al., 2019). On the other hand, there are studies that point to some LM tools that, if applied without any adaptation and prior analysis, can increase potential environmental impacts, such as Just-in-time (UGARTE; GOLDEN; DOOLEY, 2016).

Despite the growing number of studies that address LM and environmental sustainability, there is a gap in the literature on the application of Lean Manufacturing integrated to a more holistic view of the organization in relation to environmental sustainability. In this sense, the Circular Economy (CE) can bring this vision and few studies discuss the integration of LM with CE (SCHMITT et al., 2021).

The term CE evolved from several late 20th-century influences such as industrial ecology, natural capitalism, blue economy, and cradle-to-cradle, in addition to product lifecycle engineering and management (OLIVEIRA et al., 2021). It gained attention mainly in the last 5 years, and its main disseminating entity is the Ellen MacArthur Foundation, which had its first report published on the subject in 2012 (WEETMAN, 2019). The key concept of CE is based on the development of non-linear systems, as opposed to the Linear Economy of "take, produce, discard":

- Waste-free design: product design must take into account the life cycle of the materials used, and be designed for disassembly and refurbishment;
- Build resilience through diversity: it is necessary to prioritize modularity, versatility, and adaptability to diversify the system making it more resilient;
- Use energy from renewable sources: production systems must be driven by renewable energy;
- Systems thinking: understanding how parts influence each other within a whole and the relationship of the whole to the parts to create opportunities;

- Waste is food/nutrient: in living systems, all waste is used in some other way, therefore, waste must be seen as nutrient/food in biological cycles (ELLEN MACARTHUR FUNDATION, 2013).

Recent literature on the integration of LM and CE concepts points to similar objectives between them, demonstrating that LM principles and tools help in the implementation of the Circular Economy and that the integration of the two increases performance in the efficient use of resources in organizations (LIM et al., 2022).

Caldera et al. (2019), presented a model for small and medium-sized companies to develop more sustainable practices and concluded that LM helps in the implementation of CE at the manufacturing process level, reducing the use of resources and energy consumption. (CILIBERTO et al., 2021) study the relationship between Industry 4.0, LM, and CE and conclude that the philosophy of LM integrated with CE manages to align financial and sustainable objectives in product levels, manufacturing processes, and product distribution, reducing delivery times and increasing efficiency with waste reduction, in addition to adding more value to the customer. (KURDVE; BELLGRAN, 2021) apply a tool called “Green Performance Map” based on LM and CE concepts and demonstrate that it can improve the circularity of manufacturing processes. (SARTAL; OZCELIK; RODRÍGUEZ, 2020) show that the LM 5S tool can increase water use efficiency at the process level, concluding that the integration of LM and CE is beneficial and brings greater environmental and economic performance.

Despite the recent and growing literature on the integration of LM and EC, it is possible to assess that these two terms tend to bring relevant economic and environmental benefits to organizations. However, organizations need to be guided to know how to implement such integration in their processes, products, and value chain, and maturity models can provide this (CAVALCANTE DE SOUZA FEITOSA; RIBEIRO CARPINETTI; DE ALMEIDA-FILHO, 2021). Maturity models help in decision-making by presenting a strategic path that a company must follow to reach a certain goal (BERTASSINI et al., 2022).

Studies as Hines (2010), Nesensohn et al. (2016), Maasouman & Demirli (2016) and Chiera et al., 2021) proposed Maturity Models (MM) that assess and measure the maturity of LM in manufacturing industries and cells, and in construction sector, but with limited focus on sustainability issues. On the other hand, (VERRIER; ROSE; CAILLAUD, 2016) and (REIS et al., 2018) described LM’s maturity levels in terms of the level of integration between LM and sustainable production practices. All these studies assess the maturity level from an organizational point of view, i.e., give more focus on assessing and suggesting opportunities to improve managerial aspects towards a better strategic process planning to production scheduling.

Regarding LM implementation in companies, a classical reference in the topic was provided by Rother & John (2003), where the steps to implement LM are: define value, map the value stream, create flow, establish pull, and pursue perfection. Hines et al. (2010) presented different levels of maturity that later was used in other studies about LM (Figure 1). In terms of MM, the current LM literature shows that the step of "Pursue perfection" can be considered as the main activity (Chiera et al., 2021; Maasouman & Demirli, 2016; Nesensohn et al., 2016) to achieve the highest maturity level in organizations, i.e., "Way of life". In general, it can be said that a "Reactive" maturity level happens when a company push the production instead of establishing a pull flow. "Formal" level is when a company defines value and establish pull production procedures based on mapping the value stream. "Deployed" is the level when opportunities to eliminate waste are already mapped and actions are put into practice to aggregate more value in production. "Autonomous" is happening when the culture of LM can be identified, and people work to eliminate any production waste by using tools like 5S and Kaizen. Finally, "Way of life" is a level that can be supported by the pursue perfection in production and extending the lean look for the whole supply chain.

Figure 1 – Levels of LM maturity


Source: (HINES, 2010)

Bertassini et al. (2022) presented a maturity model with an application methodology to assess whether the company's culture is able to receive CE initiatives. Also, (FATIMAH et al., 2020; GOLINSKA-DAWSON; WERNER-LEWANDOWSKA; KOSACKA-OLEJNIK, 2021; KAYIKCI et al., 2022; UHRENHOLT et al., 2022) developed a Maturity Model to assess and measure the maturity of waste management, resource management, organizational issues, and supply chain needs, respectively regarding the principles of CE. All these studies assess maturity level in a life cycle perspective, but no one considered LM tools or goals to integrate LM with CE.

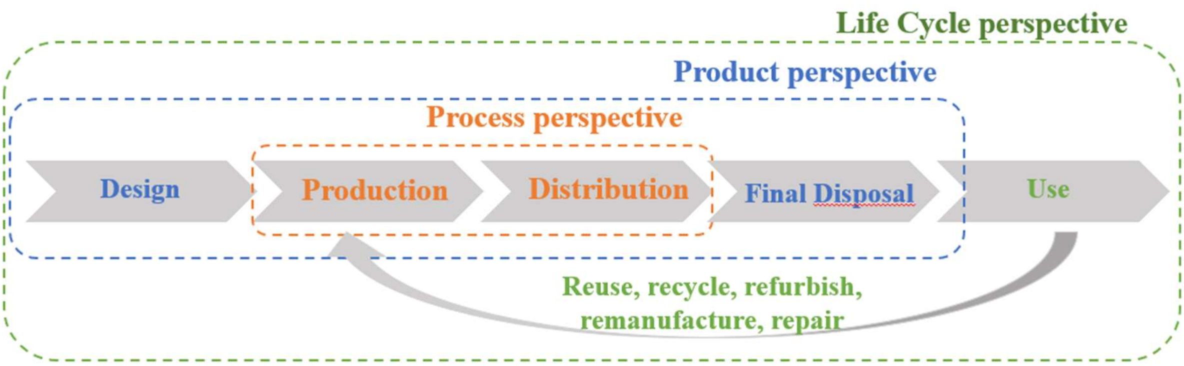
Weetman (2019) presented a four steps approach to develop CE (Figure 2). In a perspective of MMs available in literature, it can be said that the steps circular inputs, product design and process design are present (Fatimah et al., 2020; Golinska-dawson et al., 2021; Kayikci et al., 2022; Uhrenholt et al., 2022; Aguiar and Jugend, 2022). Also, the knowledge about CE is measure in these MMs (BERTASSINI et al., 2022). But no one dealt with circular flows as the highest level.

Figure 2 – Four Steps to develop CE


Source: (WEETMAN, 2019)

Considering three perspectives which combined form an entire value chain, process, product, and life cycle perspectives (Figure 3), the literature about MM in LM has a process perspective and the literature about MM in CE shows a product and life cycle perspectives. Based on this recent literature overview, it is possible to find two main gaps related to the integration of LM and EC: 1) few studies encompass the combined perspectives of MM to evaluate process, product, and life cycle thinking levels; 2) no studies were found about MM using LM and CE principles to develop more lean and circular flows. Therefore, this research intends to answer the following question: how to assess companies' maturity regarding the process, product, and life cycle to support decision-making towards the development of lean-circular flows?

Figure 3 – Three perspectives.




Source: the author (2022)

Thus, this research seeks to bring to organizations, especially those with limited financial resources, a guide for decision-making with the goal of developing circular flows based on LM and CE principles through a multicriteria approach.

## 1.2 OBJECTIVES

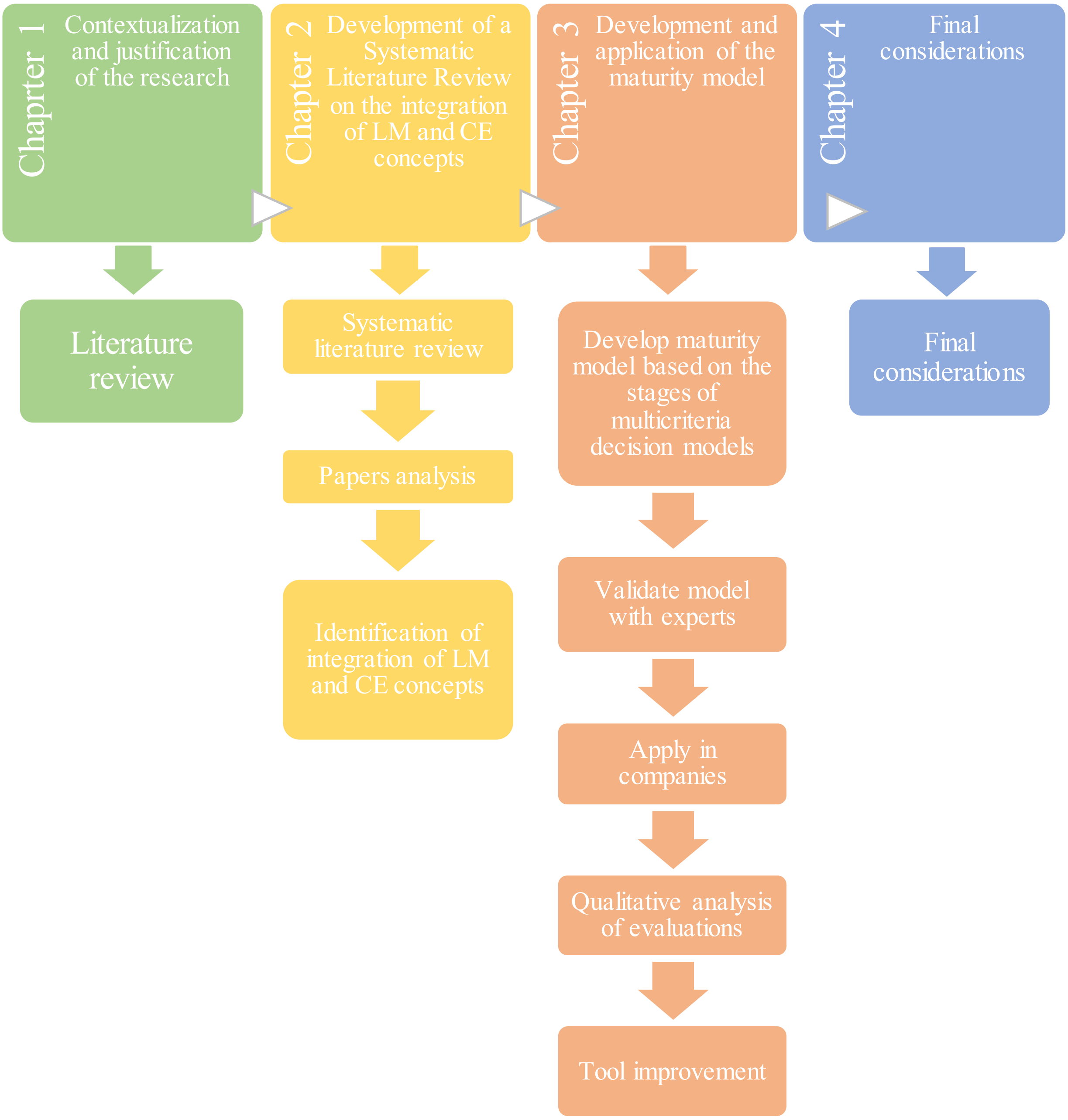
The general objective was to develop a Lean-Circular Maturity Model (LCMM) to help organizations in the self-assessment of their processes, products, and value chains. Thus, the specific objectives of this work were:

- Evaluate the current context of research carried out on the integration of LM and CE and how does such integration occur at the business levels up to company operation;
- Develop a maturity model based on LM and CE principles called LCMM;
- Apply the LCMM with organizations to validate and improve the model;
- Carry out a critical analysis of the results and compare the proposed model with the literature.

## 1.3 STRUCTURE

The structure of this work consists of a first introductory chapter and two chapters in an ‘article collection' format. It should be noted that the systematic literature review of chapter 2 was already published in the Proceedings of the XXVIII Simpósio de Engenharia de Produção (SILVA; MERGULHÃO; SILVA, 2021) and later adapted for publication in the Latin American Journal of Management for Sustainable Development (Silva et al., 2022). Figure 4 shows the structure of the work.

Figure 4 – Structure of the work.




Source: the author (2022)

## REFERENCES

BARTH, H.; MELIN, M. A Green Lean approach to global competition and climate change in the agricultural sector – A Swedish case study. **Journal of Cleaner Production**, v. 204, p. 183–192, 10 dez. 2018.

BERTASSINI, A. C. et al. CE-oriented culture readiness: An assessment approach based on maturity models and fuzzy set theories. **Sustainable Production and Consumption**, v. 31, p. 615–629, maio 2022.

CALDERA, H. T. S.; DESHA, C.; DAWES, L. Exploring the role of lean thinking in sustainable business practice: A systematic literature review. **Journal of Cleaner Production**, v. 167, p. 1546–1565, 20 nov. 2017.

CALDERA, H. T. S.; DESHA, C.; DAWES, L. Evaluating the enablers and barriers for successful implementation of sustainable business practice in 'lean' SMEs. **Journal of Cleaner Production**, v. 218, p. 575–590, 1 maio 2019.

CAVALCANTE DE SOUZA FEITOSA, I. S.; RIBEIRO CARPINETTI, L. C.; DE ALMEIDA-FILHO, A. T. A supply chain risk management maturity model and a multi-criteria classification approach. **Benchmarking**, v. 28, n. 9, p. 2636–2655, 2 nov. 2021.

CHIERA, M. et al. Lean maturity assessment in eto scenario. **Applied Sciences (Switzerland)**, v. 11, n. 9, 1 maio 2021.

CILIBERTO, C. et al. Enabling the Circular Economy transition: a sustainable lean manufacturing recipe for Industry 4.0. **Business Strategy and the Environment**, v. 30, n. 7, p. 3255–3272, 1 nov. 2021.

DE OLIVEIRA REZENDE, M. et al. A Lean and Green approach for the eco-efficiency assessment on construction sites: description and case study. **Clean Technologies and Environmental Policy**, 2022.

DIESTE, M. et al. The relationship between lean and environmental performance: Practices and measures. **Journal of Cleaner Production**, v. 224, p. 120–131, 1 jul. 2019.

ELLEN MACARTHUR FUNDATION. **Towards the Circular Economy: Economic and business rationale for an accelerated transition**. [s.l: s.n.].

FATIMAH, Y. A. et al. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. **Journal of Cleaner Production**, v. 269, 1 out. 2020.

FÓRUM ECONÔMICO MUNDIAL. **The Global Risks Report 2022**. [s.l: s.n.].

GOLINSKA-DAWSON, P.; WERNER-LEWANDOWSKA, K.; KOSACKA-OLEJNIK, M. Responsible resource management in remanufactur-ing—framework for qualitative assessment in small and medium-sized enterprises. **Resources**, v. 10, n. 2, p. 1–17, 1 fev. 2021.

HINES, P. How to create and sustain a lean culture. **Development and Learning in Organizations: An International Journal**, v. 24, n. 6, 5 out. 2010.

KAYIKCI, Y. et al. Assessing smart circular supply chain readiness and maturity level of small and medium-sized enterprises. **Journal of Business Research**, v. 149, p. 375–392, 1 out. 2022.

KURDVE, M.; BELLGRAN, M. Green lean operationalisation of the circular economy concept on production shop floor level. **Journal of Cleaner Production**, v. 278, 1 jan. 2021.

LEKSIC, I.; STEFANIC, N.; VEZA, I. The impact of using different lean manufacturing tools on waste reduction. **Advances in Production Engineering And Management**, v. 15, n. 1, p. 81–92, 1 mar. 2020.

LEME, R. D. et al. Creating value with less impact: Lean, green and eco-efficiency in a metalworking industry towards a cleaner production. **Journal of Cleaner Production**, v. 196, p. 517–534, 20 set. 2018.

LIM, M. K. et al. Circular economy to ensure production operational sustainability: A green-lean approach. **Sustainable Production and Consumption**, v. 30, p. 130–144, 1 mar. 2022.

MAASOUMAN, M. A.; DEMIRLI, K. Development of a lean maturity model for operational level planning. **International Journal of Advanced Manufacturing Technology**, v. 83, n. 5–8, p. 1171–1188, 1 mar. 2016.

MORALES-CONTRERAS, M. F. et al. Applying lean in process innovation in healthcare: The case of hip fracture. **International Journal of Environmental Research and Public Health**, v. 17, n. 15, p. 1–25, 1 ago. 2020.

NESENSOHN, C.; BRYDE, D. J.; PASQUIRE, C. A Measurement Model for Lean Construction Maturity. **Lean Construction Journal**, p. 1–9, 2016.

OHNO, T. **O Sistema Toyota de Produção**. [s.l: s.n.].

OLIVEIRA, J. A. et al. **Life Cycle Engineering and Management of Products**. Cham: Springer International Publishing, 2021.

RAMOS, A. R. et al. A lean and cleaner production benchmarking method for sustainability assessment: A study of manufacturing companies in Brazil. **Journal of Cleaner Production**, v. 177, p. 218–231, 10 mar. 2018.

REIS, L. V. et al. A model for Lean and Green integration and monitoring for the coffee sector. **Computers and Electronics in Agriculture**, v. 150, p. 62–73, 1 jul. 2018.

RIBEIRO, M. A. S. et al. Analysis of the Implementation of the Single Minute Exchange of Die Methodology in an Agroindustry through Action Research. **Machines**, v. 10, n. 5, p. 287, 20 abr. 2022.

ROTHER, M.; JOHN, S. **Learning to See: Value Stream Mapping to Add Value and Eliminate MUDA**. [s.l: s.n.].

SARTAL, A.; OZCELIK, N.; RODRÍGUEZ, M. Bringing the circular economy closer to small and medium entreprises: Improving water circularity without damaging plant productivity. **Journal of Cleaner Production**, v. 256, 20 maio 2020.

SCHMITT, T. et al. Beyond "Leanear" production: A multi-level approach for achieving circularity in a lean manufacturing context. **Journal of Cleaner Production**, v. 318, 10 out. 2021.

SILVA, M. H. DE P.; MERGULHÃO, R. C.; SILVA, D. A. L. **INTEGRAÇÃO DOS CONCEITOS PRODUÇÃO ENXUTA E ECONOMIA CIRCULAR - REVISÃO SISTEMÁTICA DA LITERATURA**. XXVIII Simpósio de Engenharia de Produção. **Anais**...2021.

UGARTE, G. M.; GOLDEN, J. S.; DOOLEY, K. J. Lean versus green: The impact of lean logistics on greenhouse gas emissions in consumer goods supply chains. **Journal of Purchasing and Supply Management**, v. 22, n. 2, p. 98–109, 1 jun. 2016.

UHRENHOLT, J. N. et al. Maturity Model as a Driver for Circular Economy Transformation. **Sustainability (Switzerland)**, v. 14, n. 12, 1 jun. 2022.

VERRIER, B.; ROSE, B.; CAILLAUD, E. Lean and Green strategy: The Lean and Green House and maturity deployment model. **Journal of Cleaner Production**, v. 116, p. 150–156, 10 mar. 2016.

WEETMAN, C. **Economia Circular: conceitos e estratégias para fazer negócios de forma mais inteligente, sustentável e lucrativa**. 1. ed. São Paulo: [s.n.].

WICKRAMASINGHE, G. L. D.; WICKRAMASINGHE, V. **Implementation of lean production practices and manufacturing performance: The role of lean duration**. **Journal of Manufacturing Technology Management**Emerald Group Publishing Ltd., , 2017.

WOMACK, J. P.; JONES, D. T. Lean Thinking—Banish Waste and Create Wealth in your Corporation. **Journal of the Operational Research Society**, v. 48, n. 11, p. 1148–1148, 20 nov. 1997.

WOMACK, J. P.; JONES, D. T.; ROOS, D. **A máquina que mudou o mundo**. [s.l: s.n.].

ZEKHNINI, K. et al. A model integrating lean and green practices for viable, sustainable, and digital supply chain performance. **International Journal of Production Research**, 2021.

# 2. INTEGRATION OF THE CONCEPTS LEAN MANUFACTURING AND CIRCULAR ECONOMY - SYSTEMATIC LITERATURE REVIEW

**Abstract:** With increasing concern about the negative impacts of human beings on the environment, consumers and politics are pressing organizations to make their businesses and operations more sustainable. The current literature already gives attention to the integration between circular economy (CE) and lean manufacturing (LM) to help companies in this transformation. However, there are still gaps in research terms to be addressed. Therefore, this paper aims to identify, evaluate, and describe the interactions between CE and LM through a systematic literature review. The results showed studies that focus on using LM tools to reduce environmental impacts, and the most used tool is value stream mapping. And just one disagreement was found: just-in-time and the potential to increase the emissions of greenhouse gas releases in manufacturing. However, there is beneficial integration between the environmental and economic performance of productive processes and supply chains.

**Keywords:** lean thinking; green manufacturing; circularity; theoretical review; lean tools; lean and green; sustainable development; sustainable indicators; sustainability; 9R.

## 2.1 INTRODUCTION

For a long time, companies were only concerned with meeting customer needs and increasing people's living standards to remain competitive in the market. However, there is currently a growing awareness of the negative impact of human beings on the environment (Sartal et al., 2020). Consumers started to look for companies that guarantee reasonable prices, good quality, and short-term, but are also aligned in developing environmental sustainability in their businesses and operations (Caiado et al., 2018). To continue competing in the market, companies need to seek these results to meet consumer demands and comply with the strictest policies and regulations (Leme et al., 2018; Silva et al., 2022).

Briefly, after World War II, companies introduced lean manufacturing (LM) from the need to make the operations of Japanese companies more efficient through waste reduction (Womack, 2004). It originated in the Toyota Production System through the pillars developed by Eiji Toyoda and Taiichi Ohno and is based on eliminating waste in the production system. It offers a set of tools and practices that seek the continuous improvement of operations (Powell et al., 2013).

The LM philosophy became popular in response to the growing global concern for the environment, and sustainability was added to it through the concept of green/sustainable manufacturing (Silva et al., 2016; Cobra et al., 2015). Currently, LM is recognized worldwide for its success in improving manufacturing operations, generating several positive impacts for organizations, including sustainability, due to the minimization of waste in production (Kurdve and Bellgran, 2021).

Meanwhile, the term circular economy (CE) was introduced in companies from the beginning of the last decade with the objective of ‘closing the life cycle’ of products and processes by creating more value for the ‘waste’ (Ellen MacArthur Foundation, 2013). That means transforming the current linear model of extraction, use, and disposal of materials in the environment into a circular model aligned with eco-efficiency and economic profitability (Kurdve and Bellgran, 2021; Velasco-Muñoz et al., 2021). Since CE’s primary focus is to maintain the quality and value of the materials involved for as long as possible, the CE aims to minimize waste and emissions not only for a company but also by looking at its entire value chain (Minunno et al., 2018; Silva et al., 2019; Velasco-Muñoz et al., 2021).

Given the scenario in which environmental concerns are increasing, and companies seek to adapt their businesses and operations to remain competitive in the globalized market, a beneficial synergy between the LM and CE concepts can be seen. An example of this synergy is found in some ideas and tools developed within the context of LM that can help reduce the use of resources and improve the circularity of materials simultaneously (Kurdve and Belgran, 2021; Sartal et al., 2020). Therefore, LM and CE can be integrated, bringing more significant economic and environmental efficiency to a company’s business and operations, making it more competitive in the current market, and other environmental gains (Sartal et al., 2020).

Although there are already studies on the relationship and integration of LM and CE, the current literature indicates that there are still research gaps to be explored. Sartal et al. (2020) demonstrate this gap and report on the vast space for research, as existing studies only deal with some tools, practices, or integration possibilities, not covering all areas of a company and its entire value chain. Based on this, the present study aimed to continue exploring this gap by presenting a systematic review of the literature to answer the research questions: “what is the current context of research carried out at the Brazilian and global levels on the integration of LM and CE?” Furthermore, “how does such integration occur at the business levels up to company operations?”.

The remainder of the article is structured as follows. Section 2.2 presents a description of the research methodology. Section 2.3 presents the results accompanied by a discussion. Finally, Section 2.4 describes the final considerations.

## 2.2 METHODOLOGY

This research is exploratory and descriptive, as it is a little-explored and recent topic. The first phase aimed to clarify and seek literature on how the interaction between CE and LM takes place from the business model levels to the operations in companies.

A systematic literature review was performed based on the method developed in Tranfield; Denyer and Smart (2003), presenting the following phases: 1. Exploratory research on the topic; 2. Formulation of the systematic review question; 3. Development of the research protocol; 4. Location and organization of literature; 5. Selection of relevant literature from the rules stipulated in the protocol; 6. Extract data from the literature to the question asked; and 7. Analysis and report development based on the extracted data.

Table 1 - Phases of Systematic Literature Review.

| | | |
|---|---|---|
| **Phase I** | Review planning | Phases 1/2/3: Identify the need for a systematic review, prepare a proposal and as a result, develop a protocol for review |
| **Phase II** | Conducting the review | Phases 4/5/6: Initiation of the search, selection of studies, quality assessment, data extraction, and as a result, the synthesis of data collected in the studies |
| **Phase III** | Report and dissemination | Phase 7: As a result, the review report was obtained, and the search for practical evidence to answer the research question was obtained. |

Source: Adapted from TRANFIELD, DENYER and SMART (2003).

The searches were carried out in the Web of Science (WoS) and Scopus databases. The focus was given to publications starting from 2013, related to the first publications on CE topics, as proposed by the Ellen MacArthur Foundation to search for articles (Ellen Macarthur Foundation, 2013). Thus, this research period was from 2013 to June 2021.

Search for articles using the keywords “LM” and “CE” and their similar terms (Table 2). The inclusion criteria were complete, peer-reviewed journal articles in English with enough citations to be within the 80% most cited in the sample, according to a Pareto analysis for selecting the final sample of articles. Regarding the exclusion criteria, to eliminate articles in which the keywords have a meaning/context different from the one sought in this research, articles that do not contribute to characterize the integration between LM and CE, and articles that were not available for full access.

Table 2 - Search terms for this survey.

| Main Terms | Similar Terms |
|---|---|
| *Lean Manufacturing* | *Lean and Green, Lean approach, Lean production, Lean tool, Lean & Green, Lean Thinking, Lean method, Lean philosophy, Lean principle, Lean practice, Lean management* |
| *Circular Economy* | *Reverse logistics, Cradle-to-cradle, 6R, 3R, 5R, 9R, Reuse, Recycle, Recover, Redesign, Remanufacturing, Repropose, Refurbish, Repair, Rethink, Refuse* |

Table 3 presents the final search string and filters applied in the search. Finally, to select the papers, we followed the steps: 1. Remove duplicated; 2. Apply Pareto analysis and selected the papers representing 80% of the total citations; 3. Read the title and abstract to remove the documents that did not contribute to the research questions.

Table 3 - Search terms and results in WoS and Scopus databases.

| Data base | Final search string | Result |
|---|---|---|
| Scopus | (TITLE-ABS-KEY (((( reduc* W/2  energy) OR (reduc* W/2 energy) OR (reduc* W/2 material) OR (reduc* W/2 transport*) OR (reduc* W/2 emission) OR (reduc* W/2 resource) OR (reduc* W/2 "environmental impact") OR (reduc* W/2 pollution) OR (reduc* W/2 waste) OR (reus* W/2 energy) OR (reus* W/2 water) OR (reus* W/2 material) OR (reus* W/2 product) OR (reus* W/2 goods) OR (recycl* W/2 energy) OR (recycl* W/2 water) OR (recycl* W/2 material) OR (recycl* W/2 product) OR (recycl* W/2 goods) OR (recover* W/2 energy) OR (recover* W/2 water) OR (recover* W/2 material) OR (recover* W/2 product) OR (recover* W/2 goods) OR (remanufactur* W/2 product) OR (remanufactur* W/2 goods) OR (refurbish* W/2 product) OR (refurbish* W/2 goods) OR (repair* W/2 product) OR (repair* W/2 goods) OR (rethink* W/2 product) OR (rethink* W/2 goods) OR (refus* W/2 product) OR (refus* W/2 goods) OR "circular economy" OR "reverse logistic" OR "cradle-to-cradle") AND TITLE-ABS-KEY ("Lean manufacturing" OR "Lean and Green" OR "Lean approach" OR "Lean production" OR "Lean tool" OR "Lean & Green" OR "Lean Thinking" OR "Lean method" OR | 406 articles |

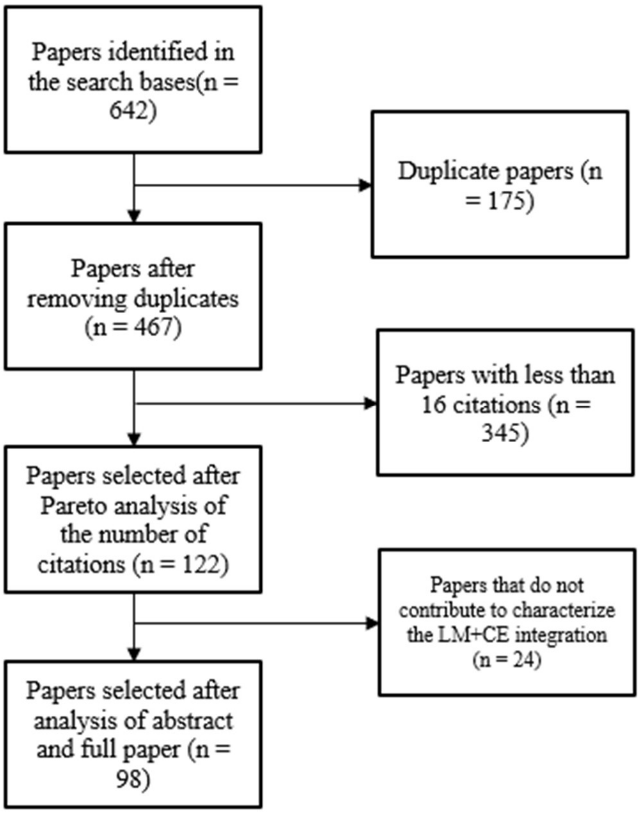
| | | |
|---|---|---|
| | "Lean philosophy" OR "Lean principle" OR "Lean practice" OR "Lean management")) | |
| WoS | (TS=((Reduc* NEAR/2 energy) OR (Reduc* NEAR/2 energy) OR (Reduc* NEAR/2 material) OR (Reduc* NEAR/2 transport*) OR (Reduc* NEAR/2 emission) OR (Reduc* NEAR/2 resource) OR (Reduc* NEAR/2 "environmental impact") OR (Reduc* NEAR/2 pollution) OR (Reduc* NEAR/2 waste) OR (Reus* NEAR/2 energy) OR (Reus* NEAR/2 water) OR (Reus* NEAR/2 material) OR (Reus* NEAR/2 product) OR (Reus* NEAR/2 goods) OR (Recycl* NEAR/2 energy) OR (Recycl* NEAR/2 water) OR (Recycl* NEAR/2 material) OR (Recycl* NEAR/2 product) OR (Recycl* NEAR/2 goods) OR (Recover* NEAR/2 energy) OR (Recover* NEAR/2 water) OR (Recover* NEAR/2 material) OR (Recover* NEAR/2 product) OR (Recover* NEAR/2 goods) OR (Remanufactur* NEAR/2 product) OR (Remanufactur* NEAR/2 goods) OR (Refurbish* NEAR/2 product) OR (Refurbish* NEAR/2 goods) OR (Repair* NEAR/2 product) OR (Repair* NEAR/2 goods) OR (Rethink* NEAR/2 product) OR (Rethink* NEAR/2 goods) OR (Refus* NEAR/2 product) OR (Refus* NEAR/2 goods) "circular economy" OR "reverse logistic*" OR "cradle-to-cradle") AND TS=("Lean manufacturing" OR "Lean and Green" OR "Lean approach" OR "Lean production" OR "Lean tool" OR "Lean & Green" OR "Lean Thinking" OR "Lean method" OR "Lean philosophy" OR "Lean principle" OR "Lean practice" OR "Lean management")) | 236 articles |

Although the search strategy with the choice of search terms aligned with the research question focused on reproducing the results, relevant papers were excluded due to the engines' limitations restricting their searches to titles, abstracts, and keywords.

## 2.3 RESULTS AND DISCUSSIONS

The filtering and selection process was conducted as shown in Figure 5. After finding 406 articles in the Scopus database and 236 articles in WoS, duplicate articles were removed, and a Pareto analysis was performed. We evaluated the most relevant results regarding the number of citations, which led to eliminating articles with less than 16 citations. 122 papers were evaluated via exclusion criteria, and 98 were selected for the final sample of the systematic literature review.

Figure 5 - Flow for selecting the sample of articles.

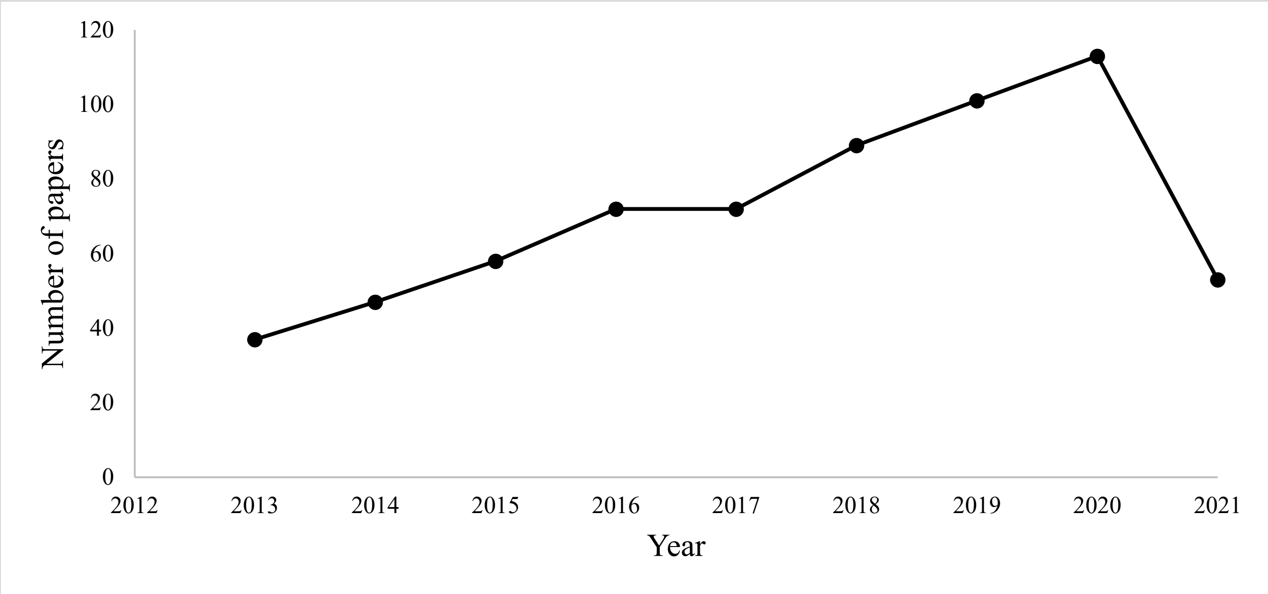



In the preliminary reading, it was possible to identify some relevant categories of analysis: year of publication, country of publication, journal, the most cited 'R' of the 9R's approach according to the CE theory, the main results achieved, and the most indicated LM and CE tools.

The results in WoS and Scopus databases identified increased publications in recent years (Figure 6), with a 205% growth from 2013 to 2020. That indicates a growing concern in reducing negative environmental impacts by integrating economic and environmental dimensions under the life cycle perspective. Also, there are external pressures on organizations from public policies and customers for better environmental performance in business and operations.

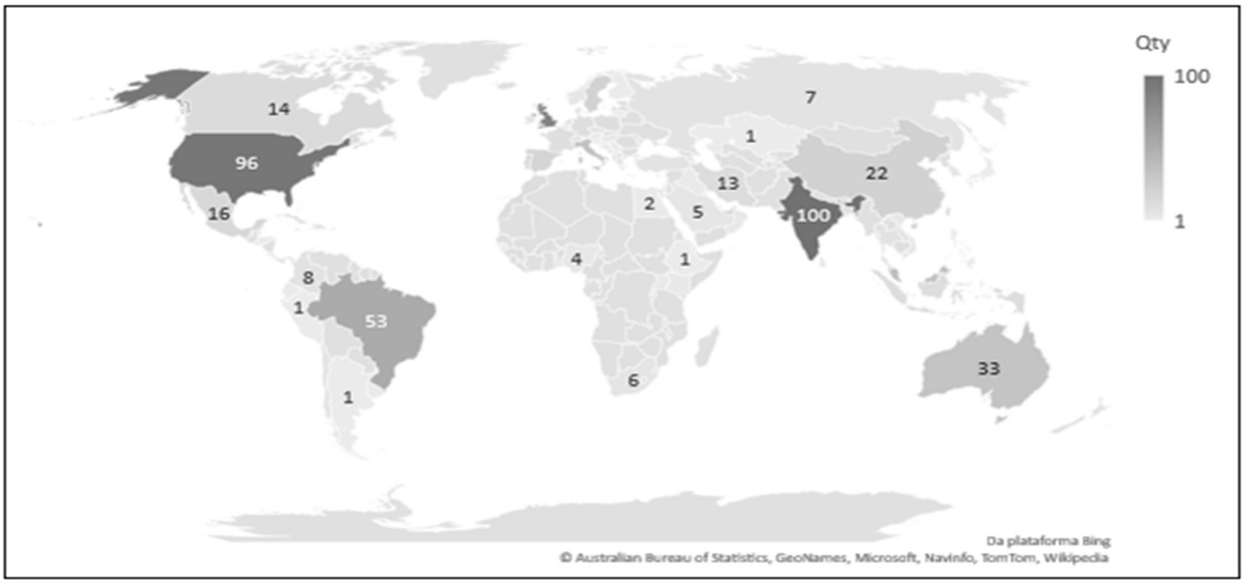
In addition, Figure 7 presents the geographical locations where the publications were produced. We considered the location information of all the authors of each publication. It was verified that the countries that stood out were India with 100 publications and the USA with 96 publications. Brazil is in fourth place with 53 related publications.

Figure 6 – The number of publications per year.




Source: data taken from WoS and Scopus (2021).

Figure 7 – The number of publications by country.

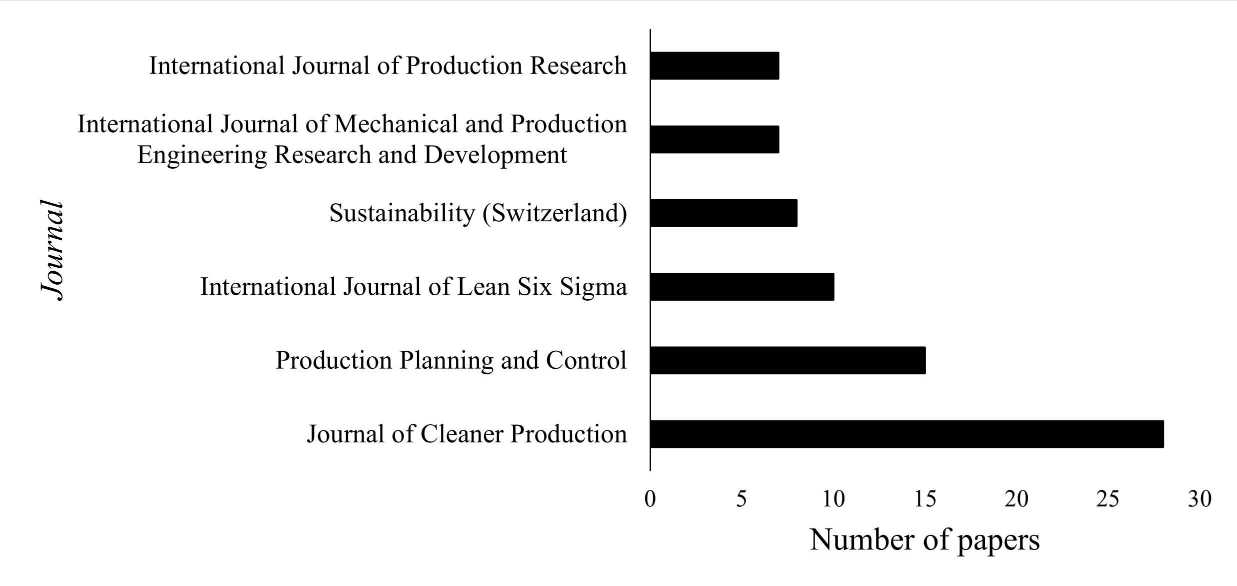



Source: data taken from WoS and Scopus (2021).

The journals that published the most on the subject can also be observed according to Figure 8. The leading journals were the Journal of Cleaner Production identified in first place with 28 publications or 4.36% of the total sample, and the Production Planning and Control in the second place, with 2.33% of the publications mapped.

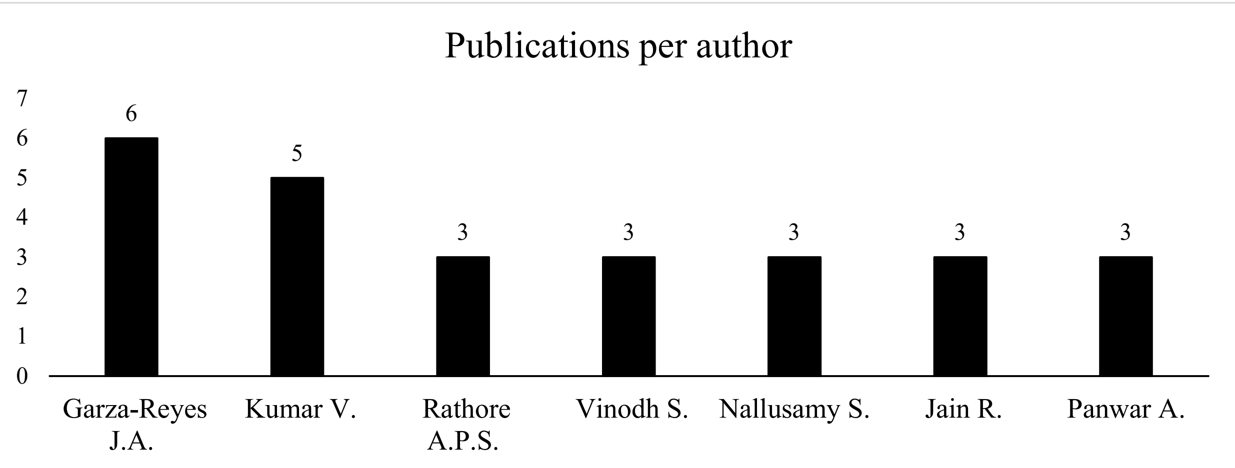
Figure 9 presents the number of publications by authors. J.A. Garza-Reyes was the most prolific one, with six papers found since 2016, with a focus on operations and production management, supply chain and logistics management, lean and agile operations and supply chains, sustainability within the context of operations and supply chains, circular or closed-loop operations and supply chains, sustainable and green manufacturing, Industry 4.0 technologies application in operations and supply chains, lean management, quality management and operations excellence, and innovation management. According to these research areas, we found that the topics of LM and CE are currently developed by this author in terms of supply chain consequences of CE adoption in applied research with companies by case studies and reviews and using LM thinking to improve the environmental and economic performance of transport and operations.

Figure 8 – The number of publications by journals.




Source: data taken from WoS and Scopus (2021).

Figure 9 – The number of publications by authors.




Source: data taken from WoS and Scopus (2021).

The second one was V. Kumar, with five published papers in the period, mainly focused on the following research areas: developing insights for international business, innovation effects of multinational enterprises, strategies to enhance customer engagement, the impact of ecommerce and m-commerce on consumer choice process, global diffusion models and marketing mix diffusion models, developing alternative methodology for product positioning and market segmentation, application of quantitative techniques to strategic planning, construction of models based on utility functions for managerial decision-making, developing decision support systems for marketing models, evaluation of the factors influencing foreign market entry, and internationalization of small businesses. This author researched lean and CE topics regarding the strategic consequences in production systems and business model effects.

The remaining 294 authors published three or fewer papers in the analysis. Therefore, based on these few numbers of papers per author, it can be seen that most of the identified authors are classified as one-timers or as incoming authors (Silva et al., 2016) in the area of LM and CE topics.

Table 4 summarizes the integration between LM and CE, in which the ten most cited articles are highlighted. This summary shows that the LM and CE integration occurs in companies' operations and aims to improve environmental and economic performance. It was possible to assess that this integration can be called 'sustainable manufacturing/production' (Caldera et al., 2017; Helleno et al., 2017) or the integration of 'lean' and 'green' (Cherrafi et al., 2017; Fercoq et al., 2016; Pampanelli et al., 2014; Thanki et al., 2016).

In Table 4, the third column presents which industry each study focused on. Most of them focused on manufacturing industries, and it was possible to find which CE cycle, i.e., technical, or biological cycle, was the primary target.

In the technical cycle, a product is manufactured using finite raw materials. It comprises the end-of-life strategies of recycling, refurbishment, remanufactures, reuse/redistribution, and maintenance/prolonging the product life cycle (Ellen MacArthur Foundation, 2013). On the other hand, the biological cycle encompasses bio-based raw materials and comprises the extraction processes of biochemical feedstocks, anaerobic digestion, regeneration, and farming/collection strategies for waste (Ellen MacArthur Foundation, 2019).

There was no study focusing on the CE's biological cycle in the ten most cited articles. Therefore, a lack of studies about LM and CE in the agricultural sector was found, as Reis et al. (2018) already reported.

Table 4 – Summary of the integration between LM and CE of the ten most cited articles in the sample.

| Author | LM and CE integration | Industry |
|---|---|---|
| Thanki S., Govindan K., Thakkar J. | Evaluation of practices to improve the performance of small or medium manufacturing companies in the requirements of cost, quality, on-time delivery, cycle time, emissions, sewage, solid waste, and energy consumption. | Manufacturing |
| Chiarini A. | Evaluation of LM tools (VSM, 5S, Cellular Manufacturing, and Total Productive Maintenance (TPM)) to reduce environmental impacts in the production system of motorcycle component companies. | Manufacturing |
| Pampanelli A.B., Found P., Bernardes A.M. | Evaluation of the implementation of LM thinking (quality, delivery, and cost, and the seven wastes) focused on environmental sustainability (reducing energy, water, resource, and chemical consumption, reducing effluent generation, metallic waste, hazardous waste, and general waste). | Manufacturing |
| Cherrafi A., Elfezazi S., Govindan K., Garza-Reyes J.A., Benhida K., Mokhlis A. | Assessment of DMAIC methodology focused on reducing environmental impacts for the development of the GL2S framework ("Lean Six Sigma and Green" integration) making improvements in the economic, environmental, and social performance. | Manufacturing and Service |
| Cai W., Lai K.-H., Liu C., Wei F., Ma M., Jia S., Jiang Z., Lv L. | Evaluation of lean thinking with the ESER ("energy-saving and emission-reduction") approach for the development of the LESER ("Lean energy-saving and emission-reduction") proposal. | Manufacturing |
| Helleno A.L., de Moraes A.J.I., Simon A.T., Helleno A.L. | Application of LM tools (VSM and Kaizen) and KPIs (OEE, water and energy consumption) to develop a method for applying the VSM with economic, social, and environmental indicators. | Manufacturing |

| | | |
|---|---|---|
| Fercoq A., Lamouri S., Carbone V. | Use the DOE (Design of Experiments) tool, the seven wastes thinking, and the 3Rs of CE (Reduce, Reuse and Recycle) to develop Waste Reduction Techniques in manufacturing processes. | Manufacturing |
| Caldera H.T.S., Desha C., Dawes L. | Use and integrate 5S tools, Cellular Manufacturing, Lean Supply Chain Management, TPM and VSM, Environmental Management System, Life Cycle Assessment, and "Triple Bottom Line", respectively from LM and CE. | Manufacturing |
| Saieg P., Sotelino E.D., Nascimento D., Caiado R.G.G. | Evaluation of the interactions of lean (principles, lean construction, lean green, environmental lean, lean eco-efficiency, waste reduction and efficient production), green (principles, waste reduction, Leadership in Energy and Environmental Design, energy generation, water reuse, environmental science, and sustainable development) and Building Information Modeling. | Construction |
| Kurilova-Palisaitiene J., Sundin E., Poksinska B. | LM tools and principles (VSM, Kanban, continuous flow, cellular layout, standardization, checklist, training, supplier partnerships) to reduce lead time. LM principles to optimize remanufacturing operations in forklift, engine, computer, and smartphone industries and filling machines. | Manufacturing |

Thanki et al. (2016), from a literature review about LM, green manufacturing, and their integration, used a multi-criteria approach for decision-making and concluded on the impact of these LM and green manufacturing practices on the performance of Indian small and medium-sized enterprises. The TPM was the essential practice for LM implementation combined with the ISO 14001 requirements for green manufacturing development at companies.

Chiarini (2014) described the environmental benefit of each LM tool. VSM implementation can map and identify opportunities to reduce environmental impacts, like leaks of oil and fumes in the atmosphere, and avoid high consumption of resources (material, energy). The 5S implementation can reduce the mistakes in separating the garbage and reduce the waste on the shop floor like greased and solvent rags generation. For example, cellular manufacturing can reduce energy consumption by lowering transportation in a local cell. SMED can also reduce energy consumption by reducing the time spent looking for components in setup activities. Finally, TPM can reduce environmental impacts by implementing daily autonomous maintenance practices in the shop-floor area.

Pampanelli et al. (2014) defended that LM could help companies achieve the best environmental performances. Cherrafi et al. (2017) used the define, measure, analyze, improve and control (DMAIC) cycle to propose a methodological framework to guide companies to implement and integrate green manufacturing, LM, and Six Sigma to improve economic, environmental, and social performance.

Cai et al. (2019) proposed lean energy-saving and emission reduction (LESER) that applies LM methods and tools with process management principles to minimize energy consumption and emissions. Helleno et al. (2017) proposed a conceptual approach for a group of sustainability indicators in the VSM tool. The abstract method was based on economics (operation cost, effective cost, stock cost, target cost process, takt cost, and level of economics sustainability), social (absenteeism, turnover, accident rate, noise level, national production rate, salary level, benefits/commission/profit, and level of social sustainability in operation and process) and environmental (electric power consumption, water consumption, harmful gases release, waste segregation, waste with traceable treatment, green production rate, environmental management system, and level of environmental sustainability in operation and process) indicators.

Fercoq et al. (2016) combined LM seven wastes (overproduction, inventory, transportation, motion, defects, over-processing, and waiting) and the reduction, reuse, and recovery (3R) of CE. This matrix showed that all wastes are related to ‘reduce’: adhering to the production schedule reduces de overproduction, inventory control reduces the obsolete materials and products, developing an optimum location reduce the packaging, management of essential parameters reduces defects, process control reduces over-processing and increase material efficiency and reducing work-in-process inventory reduce the time waiting. Three wastes related to ‘reuse’: excess production donated to charities, the introduction of re-usable packaging, and scraps reused as raw materials. Finally, two related aspects to ‘recovery’: internal recycling reduces transport, and pooling waste transport reduces environmental impact per ton of waste.

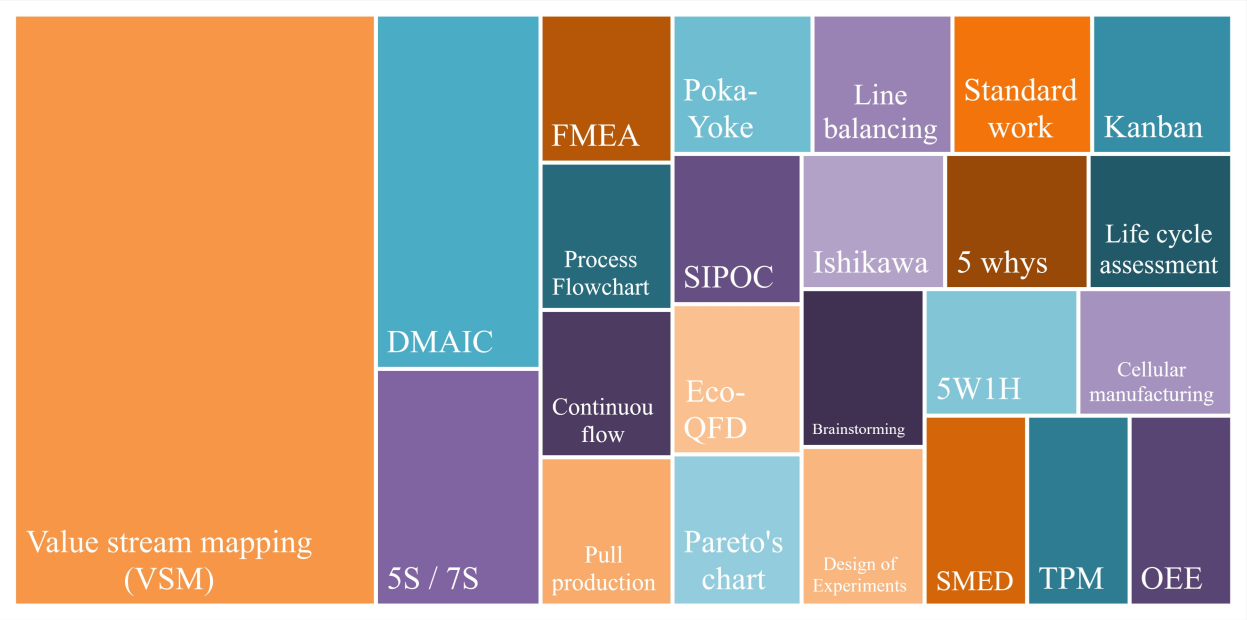
Kurilova-Palisaitiene et al. (2018) presented how LM can improve the performance of remanufacturing processes. This study shows the effect of LM-based improvements (standard operation, continuous flow, Kanban, teamwork, employing cross-training, and learning through problem-solving and supplier partnership) on the management challenges identified in remanufacturing. One of their conclusions was that LM could help improve and reduce the lead time of the remanufacturing processes.

It was possible to identify that the most cited 'R' in the 9R of the CE approach was 'reduce', accounting for 93.5% of the total related citations. Most of the papers presented integrations between the LM goals on reducing waste to increase the efficiency/eco-efficiency of production, with one of the CE goals related to reducing environmental impacts through reducing resource consumption and improved circularity materials. The most common approaches refer to reducing the consumption of water, energy, and materials and removing transport distances. 'Recycle' appeared in 3.3% of the total related citations as a vital alternative to reduce the environmental impacts of the disposed of materials.

'Reuse' appeared in 1.6% of the total related citations as an alternative to the generated waste treatment. 'Reuse' and 'remanufacture' occurred in 1.6% of the whole associated sources as a process that can increase operational performance with LM tools. Little is said about the other 'R' of the CE background, and no articles were found so far related to the combination of LM with the 'refuse', 'repair', 'refurbish', 'repurpose' and 'recover'.

Some articles presented the LM tools and how they can help to reduce environmental problems through case studies. The most adopted tool was the VSM and its derivations (Figure 10). Among the VSM derivations, we found: sustainable transportation value stream map (Garza-Reyes et al., 2016), environmental VSM (Ruben et al., 2017), transport value stream mapping (Villarreal et al., 2017), and energy value stream mapping (Baysan et al., 2019). The VSM is an LM tool and aims to map the current state of a value stream to optimize its activities by identifying activities that add value and activities that do not add value by proposing a leaner future state flow (Rother and Shook, 2007).

Figure 10 – Most used lean tools/practices in the case studies.




Source: data taken from WoS and Scopus (2021).

The first step of the sustainable transportation value stream map is mapping the road transportation process considering efficiency and environmental waste. The efficiency wastes comprise the transportation overall vehicle effectiveness (administrative availability, operation availability, performance, and quality). The CO2 and other air releases from oil and packaging materials demand per day per route. The second step is the analysis of the root causes of the wastes, and the third is the proposed future state for the transportation process (Garza-Reyes et al., 2016).

Transport value stream mapping first divides the activities into: 'not-in-transit (NIT)' and 'in-transit (IT)' activities. For NIT activities, consider the basic metrics of performance proposed by Rother and Shook (2007): cycle time, value-added time, uptime, and setup time. Furthermore, IT activities considered the average time between clients, truck capacity utilisation level, the average distance travelled per client, the distance travelled in excess per route, and the percentage of waiting time in transit. A case study showed a reduction in loading and transportation costs and diesel consumption (Villarreal et al., 2017).

Energy value stream mapping used the traditional illustration of the VSM and expanded the current state, adding new indicators related to energy: fuel/electricity consumption rates of the material handling vehicles, engine power consumption of each process, power spent for heating or cooling, at each method, and power consumption for the lighting of the area between the circles. The following steps consisted of understanding the waste and proposing a future state.

The application of this methodology resulted in a reduction in energy consumption (Baysan et al., 2019).

The VSM can reduce waste, increase the economic and environmental performance of the production process, and optimize the flow of value (Rezende et al., 2021, 2022). Rezende et al. (2022) explain that eco-efficiency indicators can be created to combine lean and green approaches at the same VSM analysis, facilitating the interpretation of the results. It is also seen as an easy-to-use tool to help companies move towards the CE when, for example, the VSM is extended beyond its point of delivery to the customer, and the life cycle of a product is considered (Hedlund et al., 2020; Marquina et al., 2021).

In this sense, Hedlund et al. (2020) proposed two parts of the value stream, the value creation flow (materials manufacturing, parts manufacturing, and product manufacturing) and the value usage flow (consumer and use, maintenance, reuse, refurbish/remanufacture), and construct a circular value stream. Marquina et al. (2021) developed a circular VSM considering economic metrics (lead time), environmental metrics (energy, water, material consumption), social metrics (physical work, level of noise, and work environment), and circular metrics (circularity and longevity) to evaluate the performance of a value stream of the refurbishment, remanufacturing, and linear process of a system. Proposed an extended VSM beyond its point of delivery to the customer.

DMAIC methodology was the second most used LM tool in the studies evaluated. DMAIC is a cycle process used to identify and solve problems, focusing on reducing variation, waste, and defects (Delgadillo et al., 2022). The integration of this LM tool with CE is related to the use to reduce environmental impacts. Ruben et al. (2017) applied a framework based on DMAIC to improve the sigma level (reduction of defects and process variation) and reduce the environmental impacts (reduction of the consumption of raw material and energy). Marrucci et al. (2020) used the methodology to collect data and information and improve the carbon footprint of food and packing waste management.

Regarding the divergent points of LM+CE integration, the just-in-time (JIT) supply chain management proposed by the LM approach is associated with higher greenhouse gas emissions in production. JIT aims to reduce inventories within the factory by increasing manufacturing flexibility; however, as a result, it often increases the frequency of deliveries and, consequently, the emission of greenhouse gases in transport (Ugarte et al., 2016).

Ugarte et al. (2016) examined the environmental impacts of lean logistics and retailing operations. Their study showed that lean logistics could increase the amount of carbon dioxide emissions, and lean retailing operations can reduce process emissions. That is also in line with

Oliveira et al. (2021). They affirm that environmental and operational performance (lead time and productivity) is not always achieved when combining LM and sustainability initiatives (e.g., cleaner production). That is a result that needs further research. For example, considering the survey of Brazilian companies by Oliveira et al. (2017), initiatives such as cleaner production help companies prepare for certifications, such as ISO 14001, also improving their environmental performance. Therefore, there are trade-offs, and such conclusions must be taken case-by-case.

However, to minimize such divergence, it would be possible, for example, to apply the sustainable transportation value stream map, which aims to increase operational efficiency in transport systems and improve environmental performance (Garza-Reyes et al., 2016). An eco-efficiency approach could be combined in the VSM tool application to map the environmental impacts (e.g., carbon footprint) before suggesting improvement opportunities in the flow (Rezende et al., 2021, 2022).

Another solution to increase the benefits of the integration of LM and CE is to conduct a diagnostic to understand what the company needs to integrate LM and CE concepts and tools effectively. Cherrafi et al. (2021) developed a self-assessment model to evaluate an organization's readiness to implement projects to reduce environmental impacts using LM.

Table 5 – Summary of LM tools and CE's 9R

| | | CE's 9R | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Recover | Recycle | Repurpose | Remanufacture | Refurbish | Repair | Reuse | Reduce | Rethink | Refuse |
| LM tools | VSM | ☹ | 😐 | ☹ | ☺ | ☹ | ☹ | 😐 | ☺ | ☹ | ☹ |
| | DMAIC / Lean Six Sigma | ☹ | 😐 | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | 5S/7S | ☹ | ☺ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | FMEA | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Process flowchart | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Continuous flow | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Pull production | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Poka-Yoke | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Line balancing | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Standard work | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Kanban | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | SIPOC | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Eco-QFD (Eco-Quality Function Deployment) | ☹ | 😐 | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Pareto's chart | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Ishikawa | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | 5 whys | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Brainstorming | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Design of Experiments | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | 5W1H | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | Cellular manufacturing | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | SMED | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | TPM | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |
| | OEE | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☹ | ☺ | ☹ | ☹ |

☹ - Tool application not found; 😐 - Found some applications of the tool; ☺ - It was found many applications of the tool to achieve the corresponding “R”.

Finally, we summarize in Table 5 the relationship of LM tools with the CE’s 9R based on the discussions found in the literature.

The results in Table 5 show that VSM, 5S/7S, continuous flow, standard work, and Kanban, which represent 21.7% of LM tools, follow at least two CE principles (☺), mainly when evaluating reduce (23 of 23 tools), remanufacture (4 of 23 tools), and recycle (1 of 23 tools) from CE principles. In addition, considering exactly two concordances (☺) or (😐) with CE principles, DMAIC/lean Six Sigma and eco-QFD, the LM tools appear with 8.7% (2 of 23) of representation when evaluating reduce (23 of 23 tools), and recycle (2 of 23 tools) from CE principles.

Otherwise, 69.6% (16 of 23) of LM tools with no relationship (☹) with CE principles in literature. The VMS, 5S/7S, continuous flow, standard work, and Kanban were the most indicated LM tools (☺) to achieve CE in practice. Therefore, there is an opportunity to enhance more knowledge in the integration of LM with CE in terms of the following tools: VSM, 5S/7S, continuous flow, standard work, Kanban, DMAIC/lean Six Sigma, and eco-QFD.

After analysis from Table 5, we evaluated that some LM tools could be more explored to support the 'R' from CE. VSM is strongly related to CE and has extended literature. Still, it could be more used in case studies associated with other 'R' (recover, recycle, repurpose, refurbish, repair, reuse, rethink, and refuse) by extending the tool to the product's life cycle perspective (Hedlund et al., 2020). DMAIC also be used more in case studies to develop projects that support recovery, recycling, repurposing, remanufacturing, refurbishing, repairing, reusing, rethinking, and refusing since this tool improves the quality of management (Wang et al., 2022).

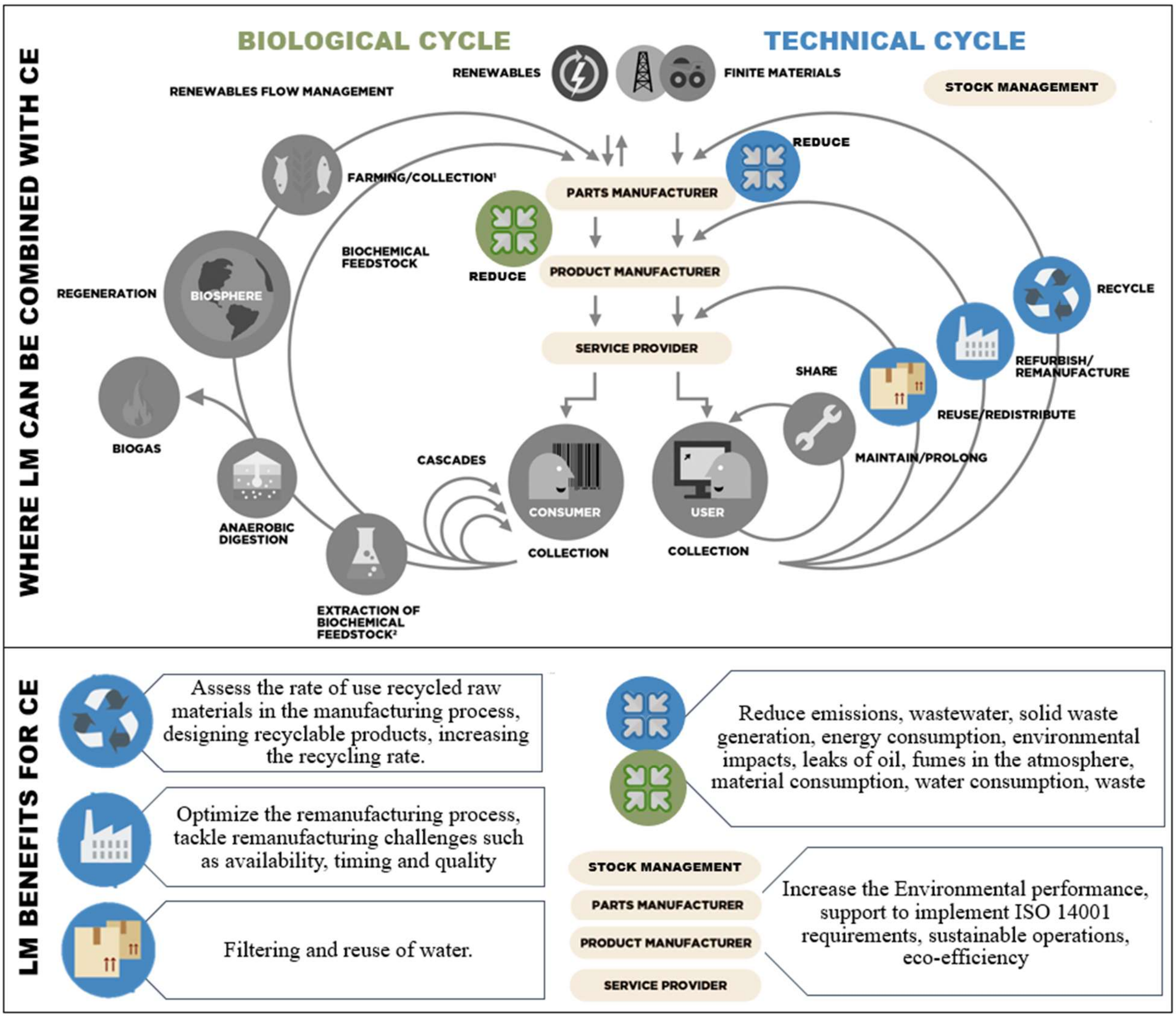
TPM and OEE positively integrate with sustainability (García Alcaraz et al., 2022; Leme et al., 2018). They could be related to remanufacturing, because they can optimize the remanufacturing process by reducing downtime and speed losses (Almeanazel, 2010) and repair (maintain/prolong) because of their focus on preventive maintenance (Hardt et al., 2021).

5S/7S can contribute to the CE principle of reduce, by reducing environmental impact. Still, it could also contribute to the principle of reuse: materials can be reused if organized in a standard way (Shahriar et al., 2022). The CE principle of remanufacture has a positive synergy with LM, also called 'lean remanufacturing'. The process of remanufacturing could be combined with LM tools such as 5S/7S to prevent wasting time looking for some material or tool, and cellular manufacturing to reduce the time (Pawlik et al., 2022).

Last but not least, we adapted the CE butterfly diagram originally developed by Ellen MacArthur Foundation (2019) in Figure 11 to show an adaptation indicating where the LM could be positively used in the CE cycles and its benefits for each stage. We suggest using the main LM tools from Table 5 to this end. Note that we had to add the 'R' of 'reduce' in the stage of manufacturing ('parts manufacturer', 'product manufacturing', and 'service provider') in the biological and technical cycle.

As demonstrated in Figure 11, the current literature present that LM brings positive effects on reuse/redistribute, refurbish/remanufacture, recycle, reduce, and stock management in the technical cycle. However, more studies are required for the biological process since most publications only encompass CE's technological cycle. The proposed diagram should be disseminated among researchers and industry practitioners to facilitate the correct and faster adoption of LM and CE.

Figure 11 – Butterfly diagram highlighting where LM can be combined with CE and its benefits.




Source: adapted from Ellen Macarthur Foundation (2019).

Thus, it can be said that the LM contributes to the EC, but given the limitations presented by the proposed diagram. Therefore, just deploying LM in the industry may not be enough to create fully circular production systems. This is in line with prior studies (Cobra et al., 2015; Silva et al., 2016; Oliveira et al., 2022), concluding that LM does not necessarily mean being 'green' or more circular. It depends on the level of implementation and maturity of LM in a company by the LM tools chosen for performance (Table 5) and the CE focus area, as illustrated in Figure 7.

## 2.4 FINAL CONSIDERATIONS

It was possible to conclude that the LM approaches focused on waste reduction and production efficiency integrated with CE have grown in the last few years. Asia and Europe are the continents that stand out the most in research.

There are more convergent than divergent topics among the approaches; therefore, LM+CE is a positive and synergistic integration for adoption by companies seeking to become more sustainable, with particular attention to the industries under the technical cycle of CE. The convergences are related to reducing adverse environmental impacts that also generate negative financial impacts, such as reducing the consumption of water, energy, and materials resources. The divergence lies in using the JIT principle because it does not look at sustainability itself and can generate an increase in greenhouse gas emissions, for example.

According to the current case studies, the backbone in combining LM with CE seems to be the VSM tool application, adapted with environmental indicators. Moreover, with the LM+CE integration, the companies today give more attention to the evaluation of industrial operations to make them more circular. Still, a more holistic view is required to make the business more sustainable, i.e., include a value chain perspective and expand the case studies to involve biological cycle initiatives. Finally, we found some gaps in the literature. Most of the studies that we found explain the benefits of LM tools to reduce environmental impacts and that companies' integration and synergy between LM and CE is positive. Some of them proposed the VSM tool to help companies find how they can start and make decisions towards a more eco-efficient value stream. However, no one shows how a company can integrate the concepts of LM and CE and build an action plan toward a more sustainable business. Also, most of the studies focused on the technical cycle of the CE and did not explore how LM can help in the biological cycle. Some of the main related LM tools could be more useful if explored on how to support the CE implementation.

This study is limited to evaluating the economic and environmental contributions of the revised articles, excluding social factors. Also, the studied sample was selected based on the number of citations per publication, excluding potential more recently published articles in the analysis.

**Acknowledgments**: The authors are grateful for grants provided by CNPq "Conselho Nacional de Desenvolvimento Científico e Tecnológico" reference numbers 302722/2019-0 and 303343/2022-2.

**REFERENCES**


Almeanazel, O.T.R. (2010) 'Total productive maintenance review and overall equipment effectiveness measurement', Jordan Journal of Mechanical and Industrial Engineering, Vol. 4, No. 4, pp.517–522.

Baysan, S., Kabadurmus, O., Cevikcan, E., Satoglu, S.I. and Durmusoglu, M.B. (2019) 'A simulation-based methodology for the analysis of the effect of lean tools on energy efficiency: an application in the power distribution industry', Journal of Cleaner Production, Vol. 211, pp.895–908 [online] https://doi.org/10.1016/j.jclepro.2018.11.217.

Cai, W., Lai, K.H., Liu, C., Wei, F., Ma, M., Jia, S., Jiang, Z. and Lv, L. (2019) 'Promoting sustainability of the manufacturing industry through the lean energy-saving and emission reduction strategy', Science of the Total Environment, Vol. 665, pp.23–32 [online] https://doi.org/10.1016/j.scitotenv.2019.02.069.

Caiado, R., Nascimento, D., Quelhas, O., Tortorella, G. and Rangel, L. (2018) 'Towards sustainability through green, lean, and Six Sigma integration at service industry: review and framework', Technological and Economic Development of Economy, Vol. 24, No. 4, pp.1659–1678.

Caldera, H.T.S., Desha, C. and Dawes, L. (2017) 'Exploring the role of lean thinking in sustainable business practice: a systematic literature review', Journal of Cleaner Production, Vol. 167, pp.1546–1565 [online] https://doi.org/10.1016/j.jclepro.2017.05.126.

Cherrafi, A., Elfezazi, S., Govindan, K., Garza-Reyes, J.A., Benhida, K. and Mokhlis, A. (2017) 'A framework for the integration of green and lean Six Sigma for superior sustainability performance', International Journal of Production Research, Vol. 55, No. 15, pp.4481–4515.

Cherrafi, A., Garza-Reyes, J.A., Belhadi, A., Kamble, S.S. and Elbaz, J. (2021) 'A readiness self-assessment model for implementing green lean initiatives', Journal of Cleaner Production, Vol. 309, p.127401 [online] https://doi.org/10.1016/j.jclepro.2021.127401.

Chiarini, A. (2014) 'Sustainable manufacturing-greening processes using specific lean production tools: an empirical observation from European motorcycle component manufacturers', Journal of Cleaner Production, Vol. 85, pp.226–233 [online] https://doi.org/10.1016/j.jclepro.2014.07.080.

Cobra, R.L.R.B., Guardia, M., Queiroz, G.A., Oliveira, J.A., Ometto, A.R. and Esposto, K.F. (2015) ''Waste' as the common 'gene' connecting cleaner production and lean manufacturing: a proposition of a hybrid definition', Environmental Quality Management, Vol. 25, pp.25–40 [online] https://doi.org/10.1002/tqem.21443.

Delgadillo, R.R., Medini, K. and Wuest, T. (2022) 'A DMAIC framework to improve quality and sustainability in additive manufacturing – a case study', Sustainability, Vol. 14, No. 1, p.581.

Ellen MacArthur Foundation (2013) Towards the Circular Economy, Economic and Business Rationale for an Accelerated Transition, pp.21–34, Ellen MacArthur Foundation, Cowes, UK.

Ellen MacArthur Foundation (2019) The Butterfly Diagram: Visualizing the Circular Economy.

Fercoq, A., Lamouri, S. and Carbone, V. (2016) 'Lean/green integration focused on waste reduction techniques', Journal of Cleaner Production, Vol. 137, pp.567–578 [online] https://doi.org/10.1016/j.jclepro.2016.07.107.

García Alcaraz, J.L., Morales García, A.S., Díaz Reza, J.R., Blanco Fernández, J., Jiménez Macías, E., Puig, I. and Vidal, R. (2022) 'Machinery lean manufacturing tools for improved sustainability: the Mexican Maquiladora industry experience', Mathematics, Vol. 10, p.1468 [online] https:// doi.org/10.3390/math10091468.

Garza-Reyes, J.A., Villarreal, B., Kumar, V. and Molina Ruiz, P. (2016) 'Lean and green in the transport and logistics sector – a case study of simultaneous deployment', Production Planning & Control, Vol. 27, No. 15, pp.1221–1232.

Hardt, F., Kotyrba, M., Volna, E. and Jarusek, R. (2021) 'Innovative approach to preventive maintenance of production equipment based on a modified TPM methodology for Industry 4.0', Applied Sciences, Vol. 11, No. 15, p.6953.

Hedlund, C., Stenmark, P., Noaksson, E. and Lilja, J. (2020) 'More value from fewer resources: how to expand value stream mapping with ideas from the circular economy', International Journal of Quality and Service Sciences, Vol. 12, No. 4, pp.447–459 [online] https://doi.org/10.1108/IJQSS-05-2019-0070.

Helleno, A.L., de Moraes, A.J.I. and Simon, A.T. (2017) 'Integrating sustainability indicators and lean manufacturing to assess manufacturing processes: application case studies in Brazilian industry', Journal of Cleaner Production, Vol. 153, pp.405–416 [online] https://doi.org/10.1016/j.jclepro.2016.12.072.

Kurdve, M. and Bellgran, M. (2021) 'Green lean operationalisation of the circular economy concept on production shop floor level', Journal of Cleaner Production, Vol. 278, p.123223 [online] https://doi.org/10.1016/j.jclepro.2020.123223.

Kurilova-Palisaitiene, J., Sundin, E. and Poksinska, B. (2018) 'Remanufacturing challenges and possible lean improvements', Journal of Cleaner Production, Vol. 172, pp.3225–3236 [online] https://doi.org/10.1016/j.jclepro.2017.11.023.

Leme, R.D., Nunes, A.O. and Silva, D.A.L. (2018) 'Creating value with less impact: lean, green and eco-efficiency in a metalworking industry towards a cleaner production', Journal of Cleaner Production, Vol. 196, pp.517–534 [online] https://doi.org/10.1016/j.jclepro.2018. 06.064.

Marquina, M.V.H., Zwolinski, P. and Mangione, F. (2021) 'Application of value stream mapping tool to improve circular systems', Cleaner Engineering and Technology, Vol. 5, p.100270 [online].

Marrucci, L., Marchi, M. and Daddi, T. (2020) 'Improving the carbon footprint of food and packaging waste management in a supermarket of the Italian retail sector', Waste Management, Vol. 105, pp.594–603 [online] https://doi.org/10.1016/j.wasman.2020.03.002.

Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L. and Colling, M. (2018) 'Strategies for applying the circular economy to prefabricated buildings', Buildings, Vol. 8, No. 9, p.125.

Oliveira, J.A., Silva, D.A.L., Guardia, M., do Nascimento Gambi, L., de Oliveira, O.J. and Ometto, A.R. (2017) 'How can cleaner production practices contribute to meet ISO 14001 requirements? Critical analysis from a survey with industrial companies', Clean Technologies and Environmental Policy, Vol. 19, No. 6, pp.1761–1774.

Oliveira, J.A.D., Devos Ganga, G.M., Godinho Filho, M., Silva, D.A.L., dos Santos, M.P., Aldaya Garde, I.A., Penchel, R.A., Esposto, K.F. and Ometto, A.R. (2022) 'Environmental and operational performance is not always achieved when combined with cleaner production and lean production: an overview for emerging economies', Journal of Environmental Planning and Management, Vol. 65, No. 8, pp.1530–1559.

Pampanelli, A.B., Found, P. and Bernardes, A.M. (2014) 'A lean & green model for a production cell', Journal of Cleaner Production, Vol. 85, pp.19–30 [online] https://doi.org/10.1016/j.jclepro.2013.06.014.

Pawlik, E., Ijomah, W., Corney, J. and Powell, D. (2022) 'Exploring the application of lean best practices in remanufacturing: empirical insights into the benefits and barriers', Sustainability, Vol. 14, p.149 [online] https:// doi.org/10.3390/su14010149.

Powell, D., Alfnes, E., Strandhagen, J.O. and Dreyer, H. (2013) 'The concurrent application of lean production and ERP: towards an ERP-based lean implementation process', Computers in Industry, Vol. 64, No. 3, pp.324–335.

Reis, L.V., Kipper, L.M., Velásquez, F.D.G., Hofmann, N., Frozza, R., Ocampo, S.A. and Hernandez, C.A.T. (2018) 'A model for lean and green integration and monitoring for the coffee sector', Computers and Electronics in Agriculture, Vol. 150, pp.62–73 [online] https://doi.org/10.1016/j.compag.2018.03.034.

Rezende, M.O., da Silva, D.V., da Silva Moris, V.A. and Silva, D.A.L. (2021) 'Lean & green and the life cycle stages of constructions: literature mapping and trend analysis', Journal of Lean Systems, Vol. 6, No. 3, pp.38–61.

Rezende, M.O., Saade, M.R.M., Nunes, A.O., da Silva, V.G., Moris, V.A.S. and Silva, D.A.L. (2022) 'A lean and green approach for the eco-efficiency assessment on construction sites: description and case study', Clean Technologies and Environmental Policy, Vol. 24, No. 5, pp.1535–1552.

Rother, M. and Shook, J. (2007) Aprendendo a Enxergar: Mapeando o Fluxo de Valor para Agregar Valor e Eliminar o Desperdício: Manual de Trabalho de Uma Ferramenta Enxuta, Lean Institute, Brazil.

Ruben, R.B., Vinodh, S. and Asokan, P. (2017) 'Implementation of lean Six Sigma framework with environmental considerations in an Indian automotive component manufacturing firm: a case study', Production Planning & Control, Vol. 28, No. 15, pp.1193–1211.

Saieg, P., Sotelino, E.D., Nascimento, D. and Caiado, R.G.G. (2018) 'Interactions of building information modeling, lean and sustainability on the architectural, engineering and construction industry: a systematic review', Journal of Cleaner Production, Vol. 174, pp.788–806 [online] https://doi.org/10.1016/j.jclepro.2017.11.030.

Sartal, A., Ozcelik, N. and Rodriguez, M. (2020) 'Bringing the circular economy closer to small and medium enterprises: improving water circularity without damaging plant productivity', Journal of Cleaner Production, Vol. 256, p.120363 [online] https://doi.org/10.1016/j.jclepro.2020.120363.

Shahriar, M.M., Parvez, M.S., Islam, M.A. and Talapatra, S. (2022) 'Implementation of 5S in a plastic bag manufacturing industry: a case study', Cleaner Engineering and Technology, Vol. 8, p.100488 [online] https://doi.org/10.1016/j.clet.2022.100488.

Silva, D.A.L., Silva, E.J.D. and Ometto, A.R. (2016) 'Green manufacturing: an analysis of scientific publications and trends for the future', Production, Vol. 26, No. 3, pp.642–655.

Silva, F.C., Shibao, F.Y., Kruglianskas, I., Barbieri, J.C. and Sinisgalli, P.A.A. (2019) 'Circular economy: analysis of the implementation of practices in the Brazilian network', Revista de Gestão, Vol. 26, No. 1, pp.39–60.

Silva, M.H.P., Costa, L.B.M., Paredes, F.J.G., Barretti, J.W. and Silva, D.A.L. (2022) 'The effect of demand forecasting choices on the circularity of production systems: a framework and case study', Resources, Conservation & Recycling Advances [online] https://doi.org/10.1016/j.rcradv.2022.200088.

Thanki, S., Govindan, K. and Thakkar, J. (2016) 'An investigation on lean-green implementation practices in Indian SMEs using analytical hierarchy process (AHP) approach', Journal of Cleaner Production, Vol. 135, pp.284–298 [online] https://doi.org/10.1016/j.jclepro.2016.06.105.

Tranfield, D., Denyer, D. and Smart, P. (2003) 'Towards a methodology for developing evidence-informed management knowledge by means of systematic review', British Journal of Management, Vol. 14, No. 3, pp.207–222.

Ugarte, G.M., Golden, J.S. and Dooley, K.J. (2016) 'Lean versus green: the impact of lean logistics on greenhouse gas emissions in consumer goods supply chains', Journal of Purchasing and Supply Management, Vol. 22, No. 2, pp.98–109.

Velasco-Muñoz, J.F., Mendoza, J.M.F., Aznar-Sánchez, J.A. and Gallego-Schmid, A. (2021) 'Circular economy implementation in the agricultural sector: definition, strategies and indicators', Resources, Conservation and Recycling, Vol. 170, p.105618 [online] https://doi.org/10.1016/j.resconrec.2021.105618.

Villarreal, B., Garza-Reyes, J.A., Kumar, V. and Lim, M.K. (2017) 'Improving road transport operations through lean thinking: a case study', International Journal of Logistics Research and Applications, Vol. 20, No. 2, pp.163–180.

Wang, Y., Zhang, S., Chi, M. and Yu, J. (2022) 'A PDCA model for disinfection supply rooms in the context of artificial intelligence to reduce the incidence of adverse events and improve the disinfection compliance rate', Journal of Healthcare Engineering, pp.1–10 [online] http://doi.org/10.1155/2022/4255751.

Womack, J.P. (2004) A Máquina que Mudou o Mundo, Publisher Campos Ltda., Brazil.

# 3. LEAN-CIRCULAR MATURITY MODEL (LCMM) FOR SELF-ASSESSMENT IN ENTERPRISES IN TERMS OF PROCESS, PRODUCT AND LIFE CYCLE MANAGEMENT

**Abstract.** There is still a gap on how Lean Manufacturing (LM) and Circular Economy (CE) can be assessed in terms of the level of maturity to help enterprises become lean-circular. In this sense, this paper developed a self-assessment to measure the maturity level in the implementation of LM and CE in companies. Using design science research, the Lean-Circular Maturity Model (LCMM) was developed covering the resources efficiency topics from a life cycle perspective. The LCMM was validated and applied in nine Brazilian companies. The results showed that 66% of the companies were looking for cleaner production alternatives before mapping their own production processes. Also, the lack of actions to manage the life cycle of products aligned with a resource's efficiency strategy can be seen as the main barrier identified. Finally, LCMM is easy to apply, provides a quick self-diagnosis and gives a list of recommendations for companies to advance their maturity.
**Keywords:** lean production, cradle-to-cradle, sustainability, maturity level, circularity

## 3.1 INTRODUCTION

Lean Manufacturing (LM) is well known as an operational mindset to reduce waste and improve quality in the production of different sectors (Kurdve & Bellgran, 2021). Also, there is a positive relationship between the implementation of LM and improvements in terms of companies' environmental performance (de Oliveira Rezende et al., 2022). More recently, LM principles have been positively related with Circular Economy (CE) applications (Lim et al., 2022), since LM can be used to reduce water, energy, and raw material consumption in a life cycle approach (De Paula e Silva et al., 2022). When LM and CE are implemented together, they can increase the creation of value in companies' processes, products, and life cycle and can be seen as a starting point to put sustainability into practice (Kalemkerian et al., 2022). Hence, LM can be a start to reduce waste to achieve the objective of the 9Rs of CE (recover, recycle, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink and refuse).

Today, companies are challenged with supporting decision-making and assessing the evolution of their progress towards sustainability (Asdecker & Felch, 2018). In this sense, Maturity Models are suitable because they aim to guide companies to improve and support their decision-making by using a maturity grid (Cavalcante de Souza Feitosa et al., 2021). Moreover, this can be seen as a way to track and report a company's progress (Asdecker & Felch, 2018).

However, there is a gap in the current literature about developing a clear diagnosis or a guide to further improvements on integrating LM and CE based on Maturity Models (De Paula e Silva et al., 2022). On one hand, previous studies have developed maturity levels for different sectors, such as construction and industry, and methods of production, such as cellular manufacturing, and engineering to order, to measure the maturity of LM in organizations (Hines, 2010; Maasouman & Demirli, 2016; Nesensohn et al., 2016). Not one of these include the environmental efficiency/performance, a life cycle perspective, or CE principles in their studies.

On the other hand, some studies have presented assessments to measure the maturity of companies' readiness to move towards a CE (Bertassini et al., 2022), the maturity in waste management practices (Fatimah et al., 2020) and in resources management in industries (Golinska-dawson et al., 2021), the progression of a company and the supply chain in the transition to a CE (Kayikci et al., 2022) and the maturity of circular product design (Aguiar & Jugend, 2022). However, the main limitation of these papers is that CE was not combined with LM. Therefore, they didn't bring the use of LM tools and principles as a pathway to create more value or synergy in the development of more sustainable/circular production systems.

Other studies focused more on economic efficiency by combining LM with Green Manufacturing (GM) (Reis et al., 2018; Verrier et al., 2016; Zekhnini et al., 2021). The main limitation of these papers was that they didn't focus on CE itself, as they did not include a life cycle perspective, nor did they evaluate the circularity of materials and/or products after manufacturing.

Despite the upcoming papers dwelling on the issue, to the best of the authors' knowledge, no previous study has addressed the assessment of the integration of LM and CE towards developing lean-circular companies so far. Moreover, most of the existing maturity models found in the literature lack a self-assessment tool to support decision-makers and guide companies towards economic and environmental efficiency from a life cycle perspective. Based on this context, this study aims to answer the question: "How to assess the maturity of LM and CE integration in companies to guide economic and environmental improvements towards lean-circular enterprises?" To answer this question, we developed a maturity model called the Lean-Circular Maturity Model (LCMM) based on an exploratory literature review and on stages of a multicriteria approach by combining scenario planning with Multi-Criteria Decision Analysis (MCDA). We applied LCMM in practice in nine companies in Brazil.

This study provides a multidisciplinary theoretical contribution since it combines MCDA, maturity model, LM and CE research topics. The maturity model developed, and the

LCMM, can guide companies in establishing targets and supporting decision-making towards economic and environmental efficiency. Moreover, we carried out a detailed application for companies from different sectors as case studies.

The remainder of the paper is structured as follows. Section 3.2 reviews the literature about LM and CE, and Section 3.3 describes the methodology used in this study based on the development procedure for the LCMM. Section 3.4 presents the results regarding the application of the LCMM, and Section 3.5 drafts a discussion about prior literature on the topic. Finally, Section 3.6 gives the final remarks of this study.

## 3.2 LITERATURE REVIEW

This section presents an exploratory literature review about LM and CE, using the keywords “lean manufacturing” and “circular economy” that we searched in SCOPUS, Web of Science and Scholar Google databases. In addition, regarding the literature review of MM in LM and CE, the keywords added were “maturity model” and “maturity assessment”.

### 3.2.1 Lean Manufacturing and Circular economy

In the last few decades, traditional LM, which focuses on the creation of value by reducing waste in manufacturing processes, took place around the environmental sustainability area with a focus on the minimization of pollution in the environment (Dieste et al., 2019). Using LM tools and principles, companies can map and reduce waste generation (De Paula e Silva et al., 2022). Positive effects in environmental and economic performance were found using LM practices with a focus on environmental sustainability by Caldera et al. (2019) in small and medium-sized enterprises (SMEs) from the secondary sector of the economy, by Dües et al. (2013) working in a production system, by Inman & Green (2018) in the manufacturing sector and by Pampanelli et al. (2014) in the production management of a cell in a manufacturing company. Value stream mapping (VSM) was indicated as the most used LM tool to reduce environmental impacts (De Paula e Silva et al., 2022). As the steps to conduct a VSM are mapping the current state using indicators and demonstrating the flow of information and materials, and then mapping a future state to optimize processes (Rother & John, 2003), it can be enhanced by the use of environmental indicators as well (Baysan et al., 2019; de Oliveira Rezende et al., 2022).

On the one hand, the combination of LM and Green/Sustainable manufacturing is limited since it takes into consideration only the process level. In other words, the boundaries are the company’s internal operations and there is not a circular vision of the process, product, and life cycle of the company's product systems (Schmitt et al., 2021). On the other hand, the literature about CE focuses on reduction of emissions and use of resources in products and their life cycle (Aguiar & Jugend, 2022; Mainardis et al., 2022).

In this sense, the integration of these two concepts, LM and CE, can develop a holistic vision of the company and increase economic and environmental performance (De Paula e Silva et al., 2022). Since this literature is recent, just a few studies have discussed this integration and there is a gap in the literature regarding this integration at a life cycle thinking level.

Reducing waste in manufacturing processes and creating value through waste in products and processes are the main positive effects of this integration (Kalemkerian et al., 2022; Lim et al., 2022; Schmitt et al., 2021). Moreover, reverse logistics and eco-design can benefit from using the LM principles by improving efficiency, increasing productivity and flexibility, and reducing lead time and complexity (Ciliberto et al., 2021; Schmitt et al., 2021). The use of the principles "reuse" and "remanufacture" can increase economic performance by generating a new business for the company, for example (Schmitt et al., 2021).

To the best of the author's knowledge, no previous study has discussed the assessment of the integration of LM and CE from a company's process, product, and life cycle perspective. This is crucial as it can assist decision-makers in developing a lean and circular company from a simpler process to a more complex value chain, incorporating a life cycle thinking perspective. Additionally, the maturity model (MM) theory could help in the development of this assessment.

### 3.2.2 Maturity models in LM and CE

It is known that the origin of Maturity Models (MM) was in 1979 with Philip B. Crosby and his Quality Management Maturity Grid (Crosby, 1980). However, the Capability Maturity Model Integration (CMMI) developed by the Software Engineering Institute (Chrissis et al., 2011) is the most recognized and widespread method for applications in different sectors.

MMs are relevant since they can support decision-makers towards an objective, indicating where they are and what the next steps are (Bertassini et al., 2022). A set of criteria in a sequence of levels is evaluated and a path to improve some areas is created by using MM (Król & Zdonek, 2020). Additionally, an MM can describe the current state and analyze where a company needs more attention (Arekrans et al., 2021).

Previous studies have developed levels and assessment tools to evaluate the maturity of LM in companies, and Table A.1 in the Supplementary Material I presents a comparison of maturity levels found in the literature.

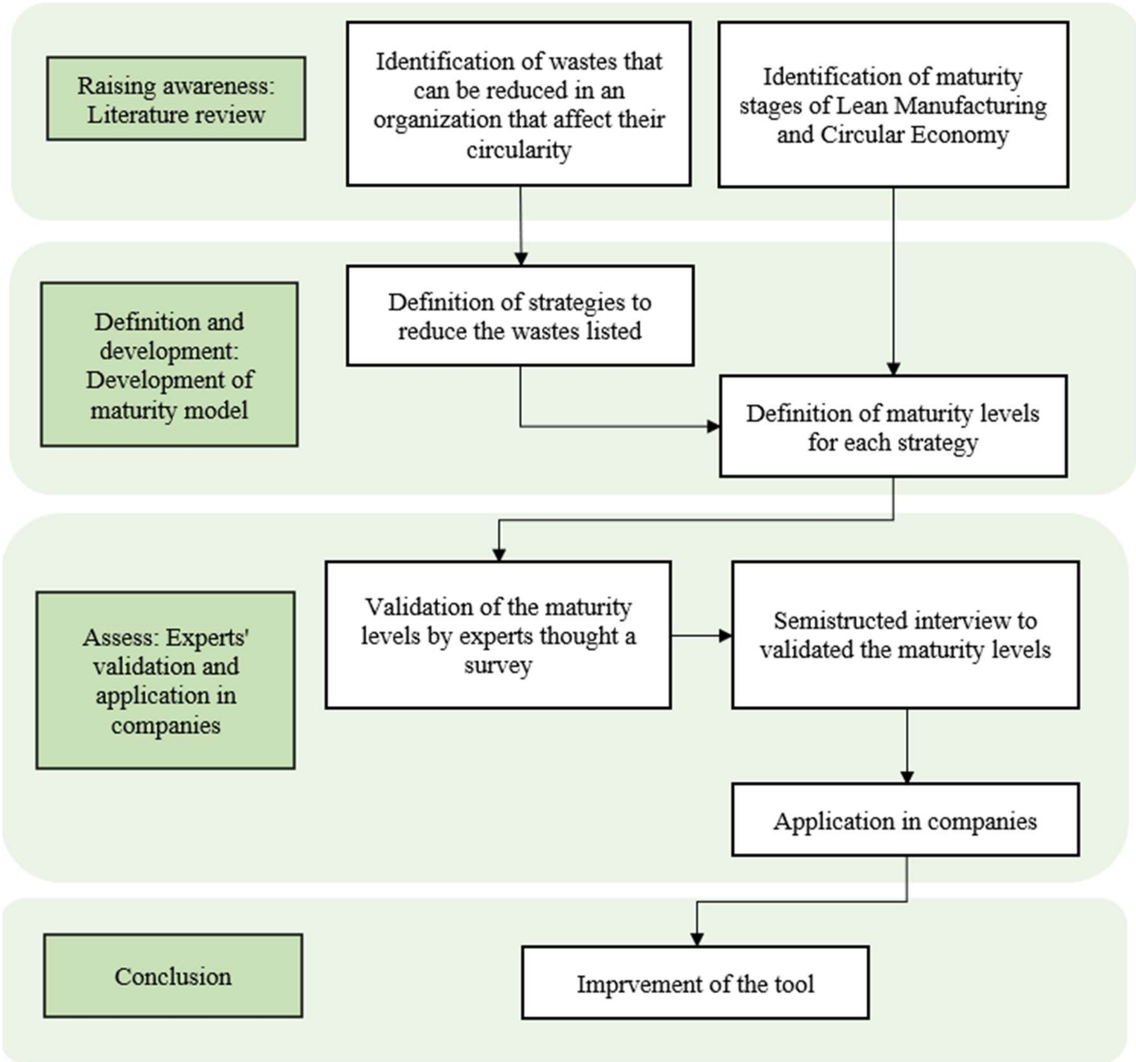
Exploratory literature review indicates that the present literature about MMs in terms of LM uses a process perspective to measure the LM's maturity in companies. Five out of six studies present that the highest level is a continuous improvement culture (Chiera et al., 2021; Hines, 2010; Maasouman & Demirli, 2016; Nesensohn et al., 2016; Verrier et al., 2016). Also, the six studies in Table A.1 developed MM for the secondary sector: manufacturing industries (Chiera et al., 2021; Hines, 2010; Jørgensen et al., 2007; Maasouman & Demirli, 2016; Verrier et al., 2016) and construction (Nesensohn et al., 2016).

Regarding CE, studies have developed levels and assessment tools to evaluate the maturity of CE in companies. Table A.2 in the Supplementary Material I Appendix A presents a comparison of maturity levels found in the literature. Five out of six studies used a life cycle perspective to measure the maturity of CE in a company (Bertassini et al., 2022; Fatimah et al., 2020; Golinska-dawson et al., 2021; Kayikci et al., 2022; Uhrenholt et al., 2022). Aguiar & Jugend (2022) used a product perspective to evaluate the maturity of CE in product design. Golinska-Dawson et al. (2021) developed their study based on the secondary sector. The remaining studies did not identify which sector they represented.

### 3.3 METHODOLOGY

The proposed LCMM was guided by design science research that has the objective of developing artifacts as a solution to practical problems (Pacheco Lacerda et al., 2013). We developed this study following the steps presented in Figure 1. For the development, validation, and application of the LCMM, we combined scenario planning with Multi Criteria Decision Analysis (MCDA), which will be covered in the next section.

Figure 12 – Structure of methodology




### 3.3.1 Development, validation, and application of LCMM

We adapted the stages from MCDA proposed by Goodwin & Wright (2005) and Ram et al. (2011) to build the LCMM. Table 1 presents the stages followed.

Table 8 – Stages proposed by our study.

| Step | Stages | Description |
|---|---|---|
| Development and Validation | 1 | Identify the objective of the maturity model |
| | 2 | Identify the strategies intended to achieve the objective from stage 1 |
| | 3 | Formulate the maturity levels |
| Application | 4 | Measure the performance for each strategy/maturity level combination |
| | 5 | Measure of robustness |

There are two macro steps in this structure, the first step was the development and validation of the LCMM, described in Stages 1 to 3. The second step was the assessment of the company's maturity level as described in Stages 4 and 5.

To develop Stages 1 and 2, and develop the maturity levels in Stage 3, an exploratory literature review was conducted as described in section 2. Also, in Stage 3 the maturity levels were formulated and the LCMM was validated by experts in the field of interest. In total, 57 experts (LM and CE researchers and consultants) were selected and contacted to answer a survey to validate LCMM developed, 12 of which answered the survey (21% of the total). Information about the experts' profile is presented in Appendix B of Supplementary Material I. After the analysis of the survey, we proposed a second version of the LCMM.

To validate the second version of the LCMM we conducted a semi-structured interview with three Brazilian experts. This semi-structured interview was online, and we asked them to evaluate and provide suggestions for the LCMM. Two of the experts have a doctorate in the areas of LM and sustainability and work in consulting. The other one has more than 10 years of experience with LM and CE in the industry. After this validation we developed a third version of the LCMM, this being the final version of the model to be applied in companies. The final version of the LCMM is available as the Supplementary Material II.

In Stages 4 and 5 we applied the LCMM, and the methodology as described in section 3.3.

### 3.3.2 Application

For Stage 4 of Table 1 we used a semi-structured questionnaire and interviewed 9 companies to measure their performance for each strategy/maturity level combination, in other words their maturity in LM and CE. We selected the companies based on exploratory research and invited them to participate in the interview. The interview was assessed by the ethical committee (CONEP – Brazil), under the process number 5526334.

The interview followed the steps presented here: 1. Initial presentation about the study: its objectives and steps; 2. Collection of information about the company; 3. Collection of information about the respondent; 4. The maturity assessment based on the model developed; 5. feedback on the LCMM and its application. After the application we analyzed the results qualitatively and quantitatively as presented in Section 4. Finally, Stage 5 of Table 1measured the level-by-level robustness of each company since this can complement maturity recommendations to advance in resource efficiency topics. In other words, if the advances forward a circular flow through a lean-circular process, product, and life cycle thinking is robust, the score in Level 1 will be higher than Level 2; Level 2 will reach a higher score than

Level 3; and in Level 3 it will be higher than in Level 4. In this sense, the metric was calculated by following the steps:

a) Calculate the difference between scores in the levels using Equations 1, 2 and 3:

$$X_1 = score\ Level\ 1 - score\ Level\ 2 \quad (1)$$

$$X_2 = score\ Level\ 2 - score\ Level\ 3 \quad (2)$$

$$X_3 = score\ Level\ 3 - score\ Level\ 4 \quad (3)$$

b) Sum the negative values.

The lower the sum in item b, the lower the final company robustness.

### 3.3.3 Development of recommendations

After the application step we provided a set of recommendations for resources efficiency in process, product and life cycle perspective by maturity level and based on the robustness results. This last step represents the main output of the LCMM to support enterprises in becoming more lean-circular.

## 3.4 RESULTS

This section presents the results of the development, validation, and application of the LCMM, and the development of recommendations.

### 3.4.1 Stage 1 – Identify the objective of the maturity model

At Stage 1, we defined the objective of the LCMM as: "Assess the maturity of LM and CE integration in companies towards circular flows with a process, product and life cycle perspective". The main characteristic of this integration of LM and CE is the reduction of waste that can result in economic and environmental efficiency (De Paula e Silva et al., 2022). Also, there are three interdependent perspectives that need to be considered in that integration: process, product, and system (Schmitt et al., 2021). Schmitt et al. (2021) explain that the "process" is composed of the sourcing, logistics and production; "product" is the research and development area, and "system" is the environmental impact beyond the company gate, i.e., the product life cycle.

### 3.4.2 Stage 2 – Identify the strategies intended to achieve the objective from stage 1

To develop the LCMM, we defined strategies to achieve the objective set in Stage 1. LM has the principle of reducing waste and increasing the activities that aggregate value to the company (Rother & John, 2003), and CE has the principle to create circular flows for the resources (Weetman, 2019). Based on this, four types of resource efficiency factors were evaluated: energy, water and wastewater, materials and solid waste, and chemicals and emissions. From this, four strategies can be seen to achieve the LCMM objectives: Energy Management, Water and Wastewater Management, Materials and Solid Waste Management, and Chemicals and Emissions Management. To complement these strategies and help companies expand their vision, we added one more strategy based on the suggestions of the specialists: Resource efficiency strategy.

### 3.4.3 Stage 3 – Formulate the maturity levels

In Table 2 and Figure 2, the developed and validated maturity levels and a scheme representing the application of the maturity levels, respectively, are described. Thus, the scenarios for the "Resource efficiency general strategy" were developed based on the stages described by the Brazilian Institute of Corporate Governance: 1. legal pre-compliance; 2. legal compliance; 3. beyond legal compliance; 4. integrated strategy; 5. purpose and passion (IBGC, 2007).

For the other topics (Energy Management, Water and Wastewater Management, Materials and Solid Waste Management, and Chemicals and Emissions Management) we proposed five levels starting with the least complex to implement and ending with the most complex to implement according to the literature (Tables A.1 and A.2 in Appendix A), and experts' opinion and experience (see Appendix B).

Level 0 means the company has nothing implemented related to LM or CE. In level 1, the company has developed key performance indicators (KPIs), and internal training for all employees related to the use of resources. For LM, the definition of a KPI is critical to create, communicate, and implement strategies and engaged employees have a significant impact on the success of these strategies (Setianto & Haddud, 2016). At level 2 the company has the resources' value stream mapping (VSM) at process level and reduces the use of resources through the principles of LM. VSM can provide an overview of the current state of the process and manage the improvement to a future state (de Oliveira Rezende et al., 2022; Salvador et al., 2021). Levels 1 and 2 represent the process perspective.

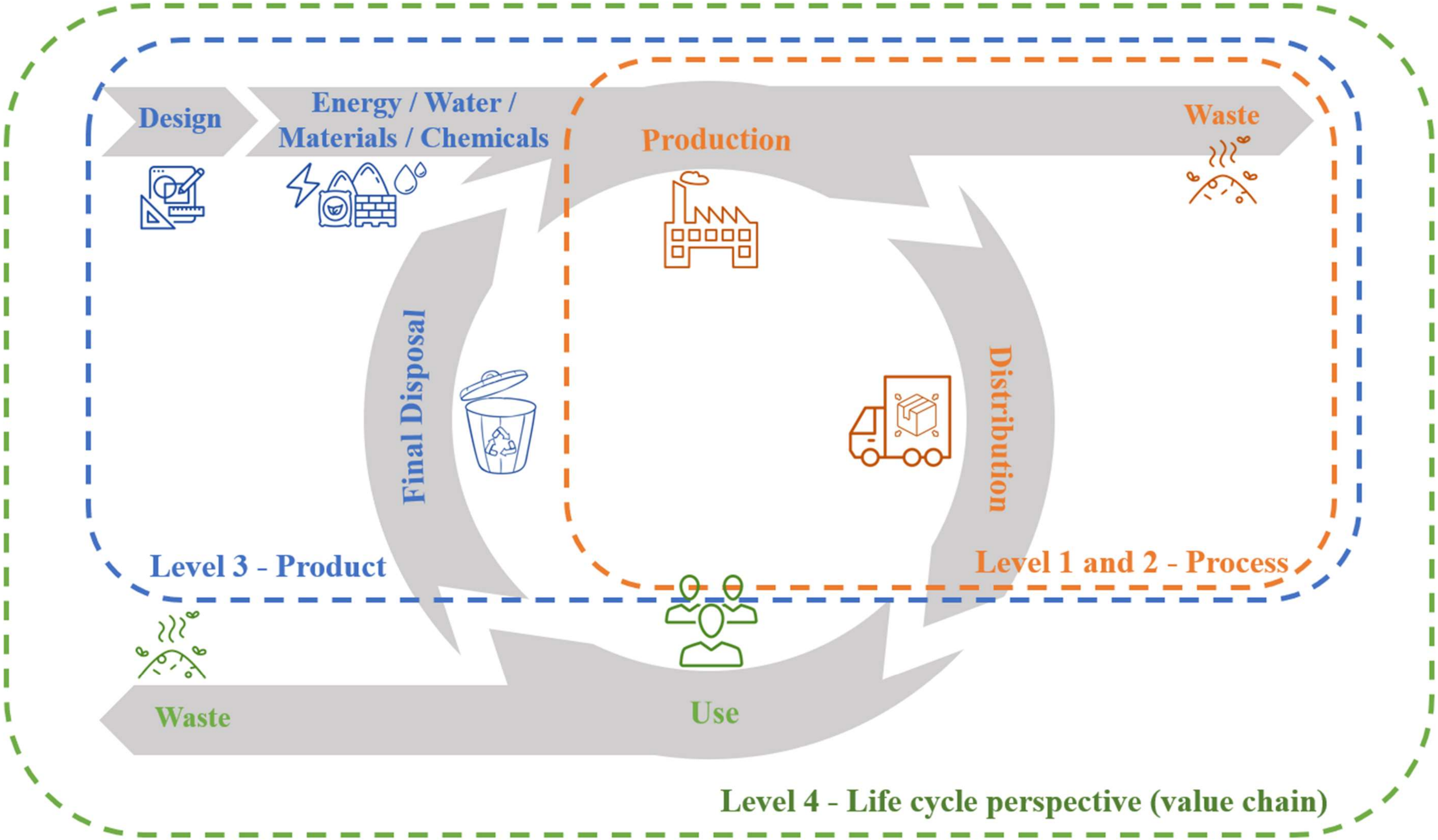
At level 3 the company continuously monitors and evaluates technological alternatives to reduce the process and product's negative impacts on the environment. The starting point to develop CE in companies is applying some principles of circularity based on circular inputs, such as the use of recycled materials, renewable sources, and reducing the use of resources in products and processes (Weetman, 2019). The principle of continuous improvement of LM can bring sustainability to the process (Maasouman & Demirli, 2016). Level 3 represents the product perspective.

At level 4 the company expands the value stream and assesses the use of resources at the life cycle level (the entire value chain). In this sense, the higher level is achieved by the daily habit of continuous improvement towards circular flows. A circular flow is achieved when the company can reuse, remanufacture or recycle the product without losing its value (Weetman, 2019). Level 4 represents the life cycle perspective.

Table 10 – Maturity levels developed and validated in Stage 3.

| Perspective | Minimum requirement | Process | | Product | Life cycle |
|---|---|---|---|---|---|
| **Topics** | **Level 0** | **Level 1** | **Level 2** | **Level 3** | **Level 4** |
| Resource efficiency general strategy | The company does not comply with environmental legislation and/or does not apply any principle of LM in its operations. | The company complies with environmental legislation and has implemented some principles of LM in its operations. | The company monitors and evaluates the efficient use of resources in its processes, identifies opportunities and applies principles of LM. | The company monitors and evaluates the efficient use of resources in its products and takes responsibility for the end-of-life strategies of its products after use. | The company presents circular flows and disseminates to its stakeholders the culture of efficient use of resources. |
| Energy Management | There are no awareness actions or energy consumption indicators in the company. | The company controls energy consumption through indicators, trains employees and raises awareness of the need to reduce energy consumption. | The company maps the energy consumption of the manufacturing and distribution stages and conducts LM principles to reduce energy consumption in these stages. | The company continuously monitors and evaluates technological alternatives that use clean/renewable energy sources and the efficiency of energy use in its products and processes. | The energy consumed by the company's entire value chain (suppliers-resources-production-distribution-use-end of life) is evaluated and actions are continuously taken to develop circular flows. |
| Water and Wastewater Management | There are no awareness actions or indicators of water consumption or wastewater disposal in the company. | The company controls water consumption and effluent disposal through indicators, trains employees and raises awareness of the need to reduce water consumption and wastewater disposal. | The company maps water consumption and wastewater disposal in the manufacturing and distribution stages and conducts LM principles to reduce water consumption and effluent disposal at these stages. | The company continuously monitors and evaluates technological alternatives that generate fewer liquid effluents and efficiency in the use of water in its products and processes, taking advantage of water through Circular Economy strategies (reuse, internal and external recycling, etc.). | The water consumed and the wastewater discarded throughout the company's value chain (suppliers-resources-production-distribution-use-end of life) are evaluated and actions are continuously taken to develop circular flows. |
| Materials and Solid Waste Management | There are no awareness actions or indicators of material consumption or solid waste disposal in the company. | The company controls the consumption of materials and the disposal of solid waste through indicators, trains employees and raises awareness of the need to reduce consumption of materials and disposal of solid waste. | The company maps material consumption and solid waste disposal in the manufacturing and distribution stages and conducts LM principles to reduce material consumption and solid waste disposal at these stages. | The company continuously monitors and evaluates technological alternatives that generate less solid waste and the efficient use of materials in its products and processes, recovering them through Circular Economy strategies (reuse, internal and external recycling, etc.). | The materials consumed and waste discarded throughout the company's value chain (suppliers-resources-production-distribution-use-end of life) are evaluated and actions are continuously taken to develop circular flows. |
| Chemicals and Emissions Management | There are no awareness actions or indicators of chemical consumption or greenhouse gas (GHG) emissions or other significant atmospheric emissions. | The company controls chemical consumption and GHG emissions, in addition to other significant atmospheric emissions, through indicators, trains employees and raises awareness. | The company maps chemical consumption and GHG emissions and other significant atmospheric emissions from the manufacturing and distribution stages and conducts LM principles to reduce chemical consumption and atmospheric emissions at these stages. | The company continuously monitors and evaluates less polluting technological alternatives and the efficiency in the use of chemicals in its products and processes, recovering them through Circular Economy strategies (reuse, internal and external recycling, etc.). | The chemicals used and GHG emissions and other significant emissions from the entire value chain (suppliers-resources-production-distribution-use-end of life) are evaluated, and actions are continuously taken to develop circular flows. |

Figure 13 – Maturity levels scheme developed and validated in Stage 3 divided into the three perspectives



### 1.1 3.4.4 Stage 4 – Measure the performance for each strategy/maturity level combination

For the development of the LCMM, we used this stage to evaluate the company's performance in each strategy/maturity level combination.

The company needs to conduct a self-evaluation considering score 0 (totally disagree) to 10 (totally agree) for each strategy/maturity level statement (Table 2). The scale 0 to 10 was selected because existing studies presented that this can be more comfortable for interviewees (Carvalho et al., 2021). Regarding the statement present in Level 0, which is a minimum requirement, if the company self-evaluate a score greater than zero, it must stop and go to the next strategy. After the self-evaluation, we applied Equation 4 rounding down to no decimal places to calculate the final level of that corresponding strategy.

$$\text{Final level} = \left(\sum \text{score from each level}\right)/10 \quad (4)$$

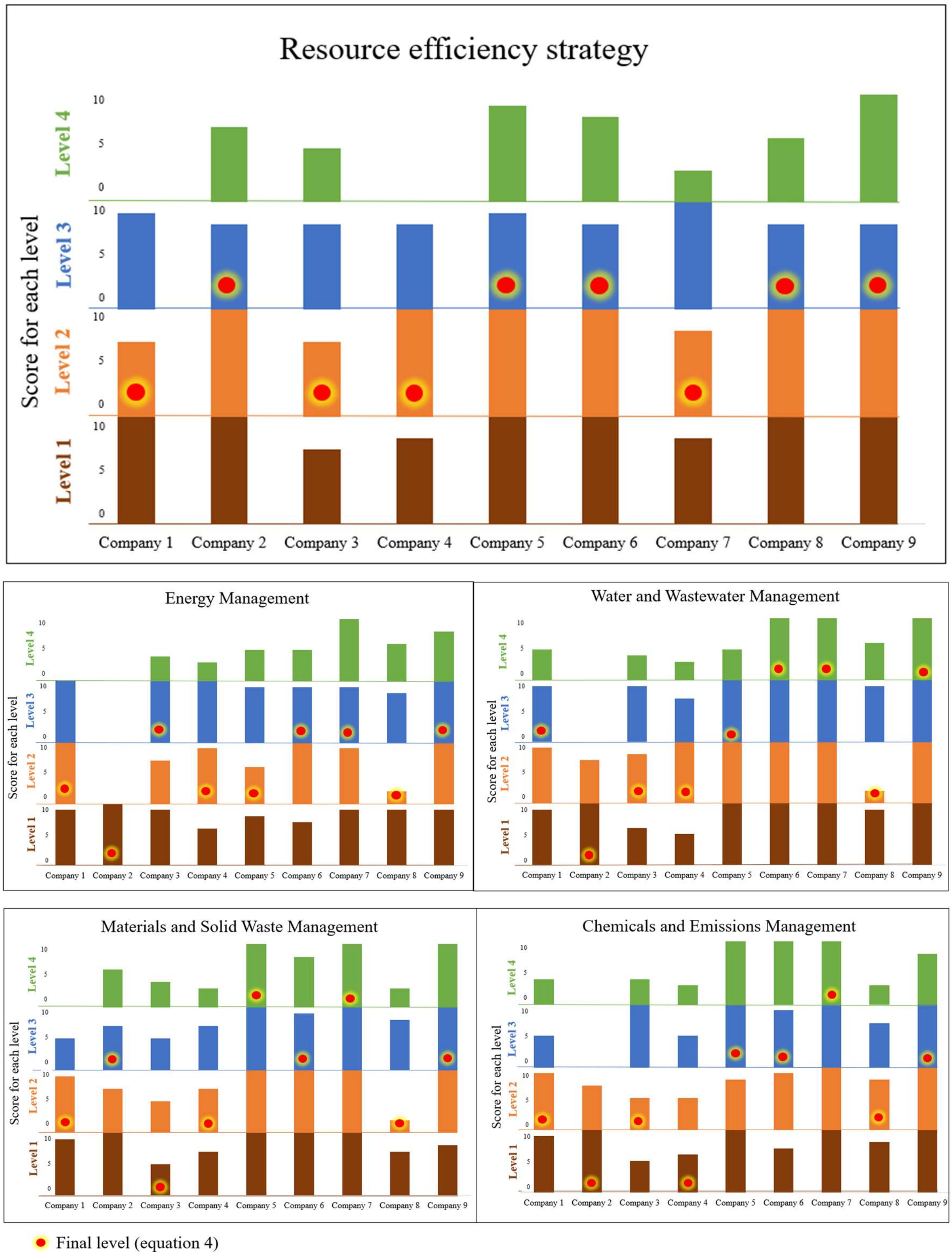
Nine companies from different sectors and sizes accepted the invitation to test the LCMM. Table C.1 in Appendix C from the Supplementary Material I presents the profile of these companies. In order to evaluate the maturity of the implementation of LM and CE, people related to these areas at the company were interviewed and asked to perform the assessment using the spreadsheet tool available online.

The results of the LCMM application can be seen in Figures 3 and 4, where the score of each level for each company is demonstrated, with the final calculated level highlighted with the support of Equation 4.

Figure 14 – Score of each company in each level for each topic of the LCMM application

Almost 67% of the total companies interviewed had the highest score in level 1 and 2 in resource efficiency strategy (Figure 14) and none of them were below score 7. In level 3, 67% answered with the score 8, 22% scored 9, and just one company self-assessed with the highest score (11%). Level 4 had the biggest variation, two answered with the lowest score (22%), three were between scores 3 and 6, four between 7 and 9, and just one company self-assessed with the highest score (11%). Regarding the final level, companies 2, 5, 6, 8, and 9 had the highest level (level 3) compared to others and no one achieved level 4..

Figure 15 – Score of each company in each level for energy management




Regarding Figure 3, almost 67% of the total companies interviewed had the highest score in level 1 and 2 in resource efficiency general strategy with none scoring below score 7. In level 3, 67% answered with the score 8, 22% scored 9, and just one company self-assessed with the highest score (11%). Level 4 had the biggest variation, two answered with the lowest score (22%), three were between scores 3 and 6, four between 7 and 9, and just one company self-assessed with the highest score (11%). Regarding the final level, companies 2, 5, 6, 8, and 9 had the highest level (level 3) compared to others and no one achieved level 4.

In energy management, 55% self-assessed with a score of 9 in level 1, just one answered with the highest score and no one was below 6. In level 2, 33% scored 10, four of them were between 6 and 9, 11% answered with the lowest score and 11% answered with a score of 2. Sixty seven percent of the companies scored level 3, the highest score, four were between scores 8 and 9, and just one answered 0, the lowest score. In level 4, 22% answered with the score 0, 22% scored 5, 22% scored 0, 11% scored 6, 11% scored 4, and 11% scored 3. Regarding final level companies 3, 6, 7 and 9 were on level 3 and no one achieved level 4.

Level 1 in water and wastewater management had 55% of the answers with a score of 10, 22% scored 9, 11% scored 5, and 11% scored 6. Almost the same happened in level 2, 55% scored 10, 11% scored 9, 11% scored 8, 11% scored 7 and 11% scored 2. In level 3, 44% answered with the score 10, 33% scored 9, 11% scored 7, and 11% scored 0. Thirty three percent of the companies answered with the highest score in level 4, 5 companies answered between 6 and 3, and one (11%) answered the lowest score, 0. Regarding the final level companies 6, 7, and 9 achieved level 4.

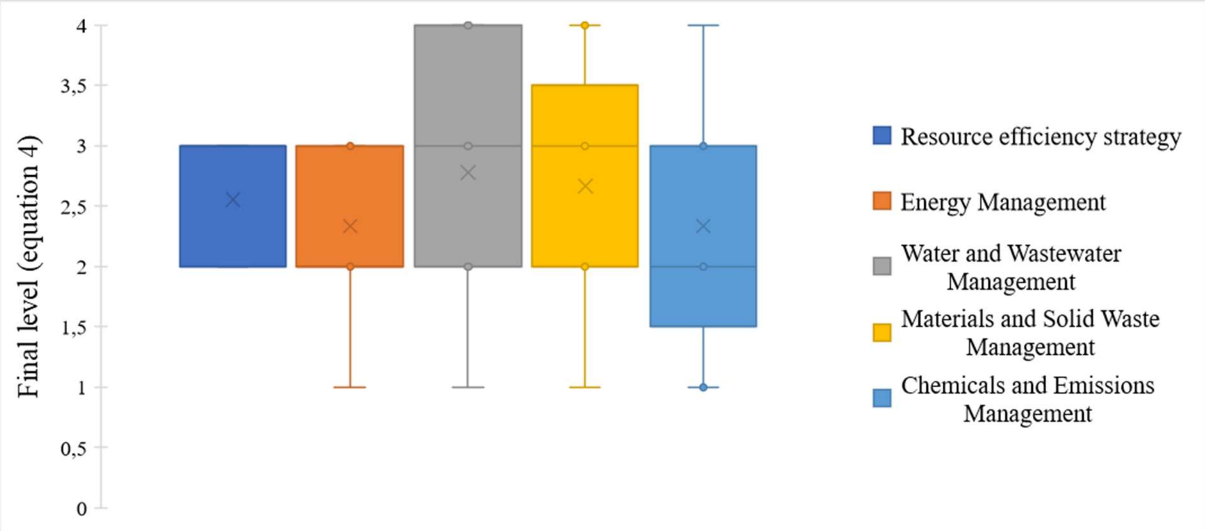
Results showed that 44% of companies achieved in materials and solid waste management the highest score in level 1. In level 2, 44% of companies stand out with a score of 10, 22% scored 7, 11% scored 9, 11% scored 5, and 11% scored 2. In level 3, 33% of the companies achieved the highest score, and the same percentage was found in level 4. Only companies 5 and 7 achieved some scores in level 4.

In chemicals and emissions management 44% of the companies answered with the score 10 in level 1, 11% scored 9, 11% scored 8, 11% scored 6, and 11% scored 5. In level 2, 22% answered with the score 10, 22% scored 9, 22% scored 8, 22% scored 5, and 11% scored 7. Forty-four percent of companies answered with the score 10 in level 3, 22% scored 5, 11% scored 9, 11% scored 7 and 11% scored 0. In level 4, 33% answered with the score 10, 22% scored 4, 22% scored 3, 11% scored 8 and 11% the lowest score, 0. Regarding the final level only company 7 achieved level 4.

In general, levels 2 and 3 represent 76% of all calculated final levels (38% each), followed by 13% of Level 4, and 11% of Level 1.

The box plot in Figure 4 shows the distribution of the levels for each strategy. We observed that the strategy of water and wastewater management had the highest final levels, and resource efficiency general strategy had the final levels between 2 and 3. In addition, energy management and resource efficiency general strategy did not have one in level 4 and the lowest final levels were in chemicals and emissions management.

Figure 19 – Distribution of the levels for each strategy




### 3.4.5 Stage 5 – Measure of robustness

Finally, following the steps to calculate the robustness presented in section 3.3.2, Table 3 presents the results. In red it highlights the negative values. The strategy for which assessment provided the lowest robustness was Energy Management since its sum was -22. In addition, the company within this strategy for which the assessment produced the lowest robustness score was company number 8, with a sum of -6. For the strategy Materials and Solid Waste Management, with a total sum of -8, 77% of companies had a robustness score of 0, representing the highest score for robustness. Furthermore, overall, the assessment of companies 3 and 8 had the lowest robustness, summing -12 and -19, respectively. The assessment of company 2 resulted in the highest robustness, summing 0. This can be explained because company 8 scored more in Level 3 than Level 2 in 60% of the strategies evaluated, while company 2 had a constant growth (e.g., Level 1 always with a better score than Level 2, Level 2 always with a better score than Level 3).

Table 12 – Robustness results

| **LCMM topic** | **Company / Robustness** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Resource efficiency general strategy | X1 | 3 | 0 | 0 | -2 | 0 | 0 | 0 | 0 | 0 | -2 |
| | X2 | -2 | 2 | -1 | 2 | 1 | 2 | -2 | 2 | 2 | -5 |
| | X3 | 9 | 1 | 3 | 8 | 0 | 0 | 7 | 2 | -2 | -2 |
| | **Total** | **-2** | **0** | **-1** | **-2** | **0** | **0** | **-2** | **0** | **-2** | **-9** |
| Energy Management | X1 | -1 | 10 | 2 | -3 | 2 | -3 | 0 | 7 | -1 | -8 |
| | X2 | 0 | 0 | -3 | -1 | -3 | 1 | 0 | -6 | 0 | -13 |
| | X3 | 10 | 0 | 6 | 7 | 4 | 4 | -1 | 2 | 2 | -1 |
| | **Total** | **-1** | **0** | **-3** | **-4** | **-3** | **-3** | **-1** | **-6** | **-1** | **-22** |
| Water and Wastewater Management | X1 | 0 | 3 | -2 | -5 | 0 | 0 | 0 | 7 | 0 | -7 |
| | X2 | 0 | 7 | -1 | 3 | 0 | 0 | 0 | -7 | 0 | -8 |
| | X3 | 4 | 0 | 5 | 4 | 5 | 0 | 0 | 3 | 0 | 0 |
| | **Total** | **0** | **0** | **-3** | **-5** | **0** | **0** | **0** | **-7** | **0** | **-15** |
| Materials and Solid Waste Management | X1 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 5 | -2 | -2 |
| | X2 | 4 | 0 | 0 | 0 | 0 | 1 | 0 | -6 | 0 | -6 |
| | X3 | 5 | 1 | 1 | 4 | 0 | 1 | 0 | 5 | 0 | 0 |
| | **Total** | **0** | **0** | **0** | **0** | **0** | **0** | **0** | **-6** | **-2** | **-8** |
| Chemicals and Emissions Management | X1 | 0 | 3 | 0 | 1 | 2 | -2 | 0 | 0 | 0 | -2 |
| | X2 | 4 | 7 | -5 | 0 | -2 | 0 | 0 | 1 | 0 | -7 |
| | X3 | 1 | 0 | 6 | 2 | 0 | -1 | 0 | 4 | 2 | -1 |
| | **Total** | **0** | **0** | **-5** | **0** | **-2** | **-3** | **0** | **0** | **0** | **-10** |

The X2 (equation 2), calculated subtracting Level 3 score from Level 2 score, has the lowest robustness, summing -39. This indicates that companies were looking for sustainable alternatives before completely mapping their processes. In this sense, we developed along with the self-assessment, a list of recommendations for each company to increase their robustness. This list is present in the next section.

### 3.4.7 Development of recommendations

To help companies in decision-making towards building circular flows we developed recommendations based on the calculated final level of maturity (Equation 4) and robustness. Based on the literature consulted in the exploratory review, we formulated recommendations (Table D.1 in Appendix D) following the levels we developed for the LCMM. When a company finishes the self-assessment diagnosis, there will be a final level and robustness index associated with each strategy. For each reference situation a specific recommendation was developed, and specific tools suggested, along with principles and concepts that could assist companies to become more lean-circular.

## 3.5 DISCUSSION

The studies about the integration of LM and CE are incipient, but the literature already shows that it can help companies to increase economic and environmental performance (Lim et al., 2022). LM is well known to assist companies by adding more value to the company's operations by reducing waste (Womack et al., 2004), and combining it with sustainable production topics can also minimize environmental impacts (Dieste et al., 2019). Combining LM with CE can bring a holistic vision, integrating economic and environmental sustainability in three main areas: process, product, and life cycle thinking in companies (Schmitt et al., 2021) resulting in the establishment of circular flows. However, due to the scarce literature addressing these three focus areas, it is difficult to have a clear vision about the path towards building circular flows using LM as a basis. In this sense, it is essential to have a clear path, as it allows decision-makers to improve company performance in an easier and faster way.

The LCMM proposed in this study allows companies to conduct a self-assessment and construct a path towards a lean and circular process, product, and life cycle thinking. By applying the self-assessment, companies become aware of their performance, what the next steps are and where their weaknesses are. It can lead to an increase of economic and environmental performance.

The results of using the LCMM showed a higher maturity in the strategy of water and wastewater management followed by the materials and solid waste management. Considering that the operations of the companies interviewed take place in Brazil, the perceived higher maturity can be related to the existence of more public policies related to these resources (water and solid waste). In addition, the robustness indicator pointed out a weakness in terms of energy management issues, where companies are developing clean energy alternatives before they have the use of energy properly mapped. This happened in all strategies as it can be seen in the calculation of X2, the maturity on Level 3 of companies is higher than that of Level 2. Another weakness regarding the robustness is between Level 1 and Level 2, where some companies did not develop training regarding the efficient use of resources that targeted all their employees, but rather only employees that directly worked with a specific topic (e.g., Continuous Improvement sector). With the results of LCMM and the robustness index, the company can also find a list of recommendations synthesized from the literature for each Level.

Regarding the theoretical implications, to the best of the authors' knowledge, there is no previous study that combines MDCA, MM, CE, and LM in a self-assessment tool. In other words, this study makes a multidisciplinary theoretical contribution as it combines different research topics in a single proposition. Furthermore, this study presents a replicable methodology that can be used to develop maturity models in different research areas. In the Supplementary Material II, we provide a copy of the developed tool to be downloaded and used free of charge.

From a practical perspective, the study presents a self-assessment process that can be used by companies in an easy way. The results of this research indicated that companies in the secondary sector can benefit more from the use of the LCMM than those from the primary and tertiary sectors. Also, for SMEs it is a free self-assessment that can be used towards a lean and circular development of the company.

Comparing the MM with the existing literature, the self-assessment proposed in this study includes a holistic vision about the company, since it presents the process, product, and life cycle perspective (Table 4). Most of the MMs found in the literature devote more attention to the process perspective and the adoption of LM principles, while a product perspective and life cycle approach are less studied. Therefore, the developed model could help overcome such limitations.

Table 14 – Comparison of the proposed MM and the previous presented in literature.

| | This proposal | Verrier et al. (2016) | Reis et al. (2018) | Cherrafi et al. (2021) | Sacco et al. (2021) | Bertassini et al. (2022) | Aguiar & Jugend (2022) |
|---|---|---|---|---|---|---|---|
| Process perspective | ☺ | ☺ | ☺ | ☺ | ☹ | ☹ | ☹ |
| Product perspective | ☺ | ☹ | ☹ | ☹ | ☺ | ☹ | ☺ |
| Life cycle perspective | ☺ | ☹ | ☹ | ☹ | ☺ | ☺ | ☺ |
| LM principles | ☺ | ☺ | ☺ | ☺ | ☹ | ☹ | ☹ |
| CE principles | ☺ | ☹ | ☹ | ☹ | ☺ | ☺ | ☺ |

## 3.6 CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH OPPROTUNITIES

This study aimed to develop and apply a self-assessment tool to guide companies in the decision-making towards establishing circular flows through the principles of LM and CE in their process, product, and life cycle. The self-assessment tool consisted of a maturity model developed through a set of stages from MCDA combined with scenario planning. The proposed MM, named lean-circular maturity model (LCMM), has five maturity levels, the strategies assessed being: Resource efficiency general strategy, Energy Management, Water and Wastewater Management, Materials and Solid Waste Management, and Chemicals and Emissions Management. The LCMM was applied in nine companies in Brazil of different sizes, sectors, and regions.

The main results showed that 66% of the companies assessed look for cleaner alternatives before identifying the opportunities, which can cause errors in the planning and hierarchization/prioritization of actions of improvement. This occurred most often in the strategy of Energy Management. Moreover, 61% of the companies presented a lack of training and awareness of all employees regarding the efficient use of resources. The lack of actions to manage the life cycle of products in the entire value chain can be seen as the main barrier identified.

Finally, the LCMM developed is easy to apply and provides a quick self-diagnosis, and a list of recommendations is provided based on the application of the LCMM and the robustness results of a company to better assist it in tracking progress in LM and CE.

Compared with prior papers in this area, it can be concluded that this paper enhances the recent theoretical knowledge regarding the integration of LM and CE. Additionally, it presented a self-assessment procedure to measure the maturity level of a process, product, or a product life cycle in companies regarding LM and CE. With a better match in the secondary sector, the LCMM can help companies to develop a clear vision of where they are now and what they need to do to become leaner and more circular. To the best of the authors' knowledge, this was the first time that a self-assessment measure was provided in terms of process, product, and from a life cycle perspective regarding the implementation of LM and CE.

Moreover, this study does not claim to be exempt from limitations. The application of the LCMM in large companies was done with just one representant in the company. In order to have a more systematic vision about the process, product, and life cycle thinking, more people from different areas should be interviewed. Also, as this research is exploratory and a new model was designed, more applications are required in different areas and sectors.

Future research opportunities include the improvement of the self-assessment to consider social aspects, application in different sectors, country and areas. Also, to the creation of a digital platform for easy use of the LCMM procedure.

**Acknowledgments**: The authors are grateful for grants provided by CNPq "Conselho Nacional de Desenvolvimento Científico e Tecnológico" reference numbers 302722/2019-0 and 303343/2022-2.

## REFERENCES

Aguiar, M. F., & Jugend, D. (2022). Circular product design maturity matrix: A guideline to evaluate new product development in light of the circular economy transition. Journal of Cleaner Production, 132732. https://doi.org/10.1016/j.jclepro.2022.132732

Arekrans, J., Ritzén, S., & Laurenti, R. (2021). Circular Economy Transitions: The Maturity of Incumbents. 22nd CINet Conference: Organising Innovation for a Sustainable Future.

Asdecker, B., & Felch, V. (2018). Development of an Industry 4.0 maturity model for the delivery process in supply chains. Journal of Modelling in Management, 13(4), 840–883. https://doi.org/10.1108/JM2-03-2018-0042

Baysan, S., Kabadurmus, O., Cevikcan, E., Satoglu, S. I., & Durmusoglu, M. B. (2019). A simulation-based methodology for the analysis of the effect of lean tools on energy efficiency: An application in power distribution industry. Journal of Cleaner Production, 211, 895–908. https://doi.org/10.1016/j.jclepro.2018.11.217

Bertassini, A. C., Calache, L. D. D. R., Carpinetti, L. C. R., Ometto, A. R., & Gerolamo, M. C. (2022). CE-oriented culture readiness: An assessment approach based on maturity models and fuzzy set theories. Sustainable Production and Consumption, 31, 615–629. https://doi.org/10.1016/j.spc.2022.03.018

Carvalho, N. L., Mendes, J. V., Akim, E. K., Mergulhão, R. C., & Vidal Vieira, J. G. (2021). Supply chain collaboration: differing perspectives of Brazilian companies. International Journal of Logistics Management, 32(1), 118–137. https://doi.org/10.1108/IJLM-10-2019-0284

Cavalcante de Souza Feitosa, I. S., Ribeiro Carpinetti, L. C., & de Almeida-Filho, A. T. (2021). A supply chain risk management maturity model and a multi-criteria classification approach. Benchmarking, 28(9), 2636–2655. https://doi.org/10.1108/BIJ-09-2020-0487

Cherrafi, A., Garza-Reyes, J. A., Belhadi, A., Kamble, S. S., & Elbaz, J. (2021). A readiness self-assessment model for implementing green lean initiatives. Journal of Cleaner Production, 309. https://doi.org/10.1016/j.jclepro.2021.127401

Chiera, M., Lupi, F., Rossi, A., & Lanzetta, M. (2021). Lean maturity assessment in eto scenario. Applied Sciences (Switzerland), 11(9). https://doi.org/10.3390/app11093833

Chrissis, M. beth, Konrad, M., & Shrum, S. (2011). Chrissis, M. B., Konrad, M., & Shrum, S. (2011). CMMI for development: guidelines for process integration and product improvement. Pearson Education.

Ciliberto, C., Szopik-Depczyńska, K., Tarczyńska-Łuniewska, M., Ruggieri, A., & Ioppolo, G. (2021). Enabling the Circular Economy transition: a sustainable lean manufacturing recipe for Industry 4.0. Business Strategy and the Environment, 30(7), 3255–3272. https://doi.org/10.1002/bse.2801

Crosby, P. B. (1980). Quality Is Free: the Art of Making Quality Certain (Vol. 2247). Signet Book.

de Oliveira Rezende, M., Saade, M. R. M., Nunes, A. O., da Silva, V. G., Moris, V. A. S., & Silva, D. A. L. (2022). A Lean and Green approach for the eco-efficiency assessment on construction sites: description and case study. Clean Technologies and Environmental Policy. https://doi.org/10.1007/s10098-021-02265-y

De Paula e Silva, M. H., Barretti, J. W., Mergulhão, R. C., & Silva, D. A. L. (2022). Integration of the concepts of lean manufacturing and circular economy: systematic literature review. Latin American J. of Management for Sustainable Development, 1(1), 1. https://doi.org/10.1504/LAJMSD.2022.10049521

Dieste, M., Panizzolo, R., Garza-Reyes, J. A., & Anosike, A. (2019). The relationship between lean and environmental performance: Practices and measures. Journal of Cleaner Production, 224, 120–131. https://doi.org/10.1016/j.jclepro.2019.03.243

Dües, C. M., Tan, K. H., & Lim, M. (2013). Green as the new Lean: How to use Lean practices as a catalyst to greening your supply chain. Journal of Cleaner Production, 40, 93–100. https://doi.org/10.1016/j.jclepro.2011.12.023

Fatimah, Y. A., Govindan, K., Murniningsih, R., & Setiawan, A. (2020). Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. Journal of Cleaner Production, 269. https://doi.org/10.1016/j.jclepro.2020.122263

Golinska-dawson, P., Werner-lewandowska, K., & Kosacka-olejnik, M. (2021). Responsible resource management in remanufactur-ing—framework for qualitative assessment in small and medium-sized enterprises. Resources, 10(2), 1–17. https://doi.org/10.3390/resources10020019

Goodwin, P., & Wright, G. (2005). Decision Analysis for Management Judgment (3rd ed.).

Hines, P. (2010). How to create and sustain a lean culture. Development and Learning in Organizations: An International Journal, 24(6). https://doi.org/10.1108/dlo.2010.08124fad.007

IBGC, I. B. de G. C. (2007). Guia de Sustentabilidade para as Empresas. www.ibgc.org.br.

Inman, R. A., & Green, K. W. (2018). Lean and green combine to impact environmental and operational performance. International Journal of Production Research, 56(14), 4802–4818. https://doi.org/10.1080/00207543.2018.1447705

Jørgensen, F., Matthiesen, R. V., Nielsen, J., & Johansen, J. (2007). Lean Maturity, Lean Sustainability. Advances in Production Management Systems, 371–378.

Kalemkerian, F., Santos, J., Tanco, M., Garza-Reyes, J. A., & Viles, E. (2022). Analysing the alignment between the Green Lean and Circular strategies: towards a Circular Lean approach. Journal of Manufacturing Technology Management. https://doi.org/10.1108/JMTM-11-2021-0480

Kayikci, Y., Kazancoglu, Y., Gozacan-Chase, N., Lafci, C., & Batista, L. (2022). Assessing smart circular supply chain readiness and maturity level of small and medium-sized enterprises. Journal of Business Research, 149, 375–392. https://doi.org/10.1016/j.jbusres.2022.05.042

Król, K., & Zdonek, D. (2020). Analytics Maturity Models: An Overview. Information, 11(3), 142. https://doi.org/10.3390/info11030142

Kurdve, M., & Bellgran, M. (2021). Green lean operationalisation of the circular economy concept on production shop floor level. Journal of Cleaner Production, 278. https://doi.org/10.1016/j.jclepro.2020.123223

Lim, M. K., Lai, M., Wang, C., & Lee, S. Y. (2022). Circular economy to ensure production operational sustainability: a gree-lean approach. Sustainable Production and Consumption.

Maasouman, M. A., & Demirli, K. (2016). Development of a lean maturity model for operational level planning. International Journal of Advanced Manufacturing Technology, 83(5–8), 1171–1188. https://doi.org/10.1007/s00170-015-7513-4

Mainardis, M., Cecconet, D., Moretti, A., Callegari, A., Goi, D., Freguia, S., & Capodaglio, A. G. (2022). Wastewater fertigation in agriculture: Issues and opportunities for improved water management and circular economy. In Environmental Pollution (Vol. 296). Elsevier Ltd. https://doi.org/10.1016/j.envpol.2021.118755

Nesensohn, C., Bryde, D. J., & Pasquire, C. (2016). A Measurement Model for Lean Construction Maturity. Lean Construction Journal, 1–9. http://researchonline.ljmu.ac.uk/

Pacheco Lacerda, D., Dresch, A., Proença, A., Valle, J. A., & Júnior, A. (2013). Design Science Research: método de pesquisa para a engenharia de produção Design Science Research: a research method to production engineering. Gestão e Produção, 20(4), 741–761.

Pampanelli, A. B., Found, P., & Bernardes, A. M. (2014). A Lean & Green Model for a production cell. Journal of Cleaner Production, 85, 19–30. https://doi.org/10.1016/j.jclepro.2013.06.014

Ram, C., Montibeller, G., & Morton, A. (2011). Extending the use of scenario planning and MCDA for the evaluation of strategic options. Journal of the Operational Research Society, 62(5), 817–829. https://doi.org/10.1057/jors.2010.90

Reis, L. V., Kipper, L. M., Giraldo Velásquez, F. D., Hofmann, N., Frozza, R., Ocampo, S. A., & Taborda Hernandez, C. A. (2018). A model for Lean and Green integration and monitoring for the coffee sector. Computers and Electronics in Agriculture, 150, 62–73. https://doi.org/10.1016/j.compag.2018.03.034

Rother, M., & John, S. (2003). Learning to See: Value Stream Mapping to Add Value and Eliminate MUDA.

Sacco, P., Vinante, C., Borgianni, Y., & Orzes, G. (2021). Circular economy at the firm level: A new tool for assessing maturity and circularity. Sustainability (Switzerland), 13(9). https://doi.org/10.3390/su13095288

Salvador, R., Barros, M. V., dos Santos, G. E. T., van Mierlo, K. G., Piekarski, C. M., & de Francisco, A. C. (2021). Towards a green and fast production system: Integrating life cycle assessment and value stream mapping for decision making. Environmental Impact Assessment Review, 87, 106519. https://doi.org/10.1016/j.eiar.2020.106519

Schmitt, T., Wolf, C., Lennerfors, T. T., & Okwir, S. (2021). Beyond “Leanear” production: A multi-level approach for achieving circularity in a lean manufacturing context. Journal of Cleaner Production, 318. https://doi.org/10.1016/j.jclepro.2021.128531

Setianto, P., & Haddud, A. (2016). A maturity assessment of lean development practices in manufacturing industry. International Journal of Advanced Operations Management, 8(4), 294–322. https://doi.org/10.1504/IJAOM.2016.084150

Uhrenholt, J. N., Kristensen, J. H., Rincón, M. C., Adamsen, S., Jensen, S. F., & Waehrens, B. V. (2022). Maturity Model as a Driver for Circular Economy Transformation. Sustainability (Switzerland), 14(12). https://doi.org/10.3390/su14127483

Verrier, B., Rose, B., & Caillaud, E. (2016). Lean and Green strategy: The Lean and Green House and maturity deployment model. Journal of Cleaner Production, 116, 150–156. https://doi.org/10.1016/j.jclepro.2015.12.022

Weetman, C. (2019). Economia Circular: conceitos e estratégias para fazer negócios de forma mais inteligente, sustentável e lucrativa (Autêntica Cusiness, Ed.; 1st ed.).

Womack, J. P., Jones, D. T., & Roos, D. (2004). A máquina que mudou o mundo.

Zekhnini, K., Cherrafi, A., Bouhaddou, I., Chaouni Benabdellah, A., & Bag, S. (2021). A model integrating lean and green practices for viable, sustainable, and digital supply chain performance. International Journal of Production Research. https://doi.org/10.1080/00207543.2021.1994164

**SUPPLEMENTARY MATERIAL I**

**Appendix A – LITERATURE REVIEW**

Table A.1 – Maturity levels for LM found in the literature.

| Authors | Level 0 | Level 1 | Level 2 | Level 3 | Level 4 | Scope |
|---|---|---|---|---|---|---|
| (Jørgensen et al., 2007) | Sporadic production optimization | Basic lean understanding and implementation | Strategic lean interventions | Proactive lean culture | Lean in the Extended Manufacturing Enterprise | Manufacturing industries, process perspective |
| (Hines, 2010) | Reactive approach | Formal structure and team learning | Deployed with Goal oriented and value stream learning | Managed autonomy with majority involvement | Way of Life with daily habit of continuous improvement and external learning | Manufacturing industries, process perspective |
| (Nesensohn et al., 2016) | Uncertain: the ideal statement is hardly evidenced in action | Awakening: general awareness exists, and the ideal statement is inconsistently in action | Systematic: the ideal statement is systemically evidenced in action | Integrated: the ideal statement is interrelated as a whole and happens automatically | Challenging: the ideal statement is status quo which is challenged to improve further | Construction sector, process perspective |
| (Verrier et al., 2016) | Initial: limited awareness of lean and green issues | Managed: occasional basic lean or green actions | Defined: regular lean and green actions (conducted separately) | Quantitatively Managed: regular lean and green actions (conducted jointly) | Optimizing: continuous optimization through lean and green symbiosis | Production process, process perspective |
| (Maasouman & Demirli, 2016) | Understanding: quantitative and qualitative progression of standardization | Implementation: deployment of tools/concepts to conduct the expected results (effectiveness) | Improvement: deployment of tools/concepts to conduct the expected results and uses | Sustainability: deployment of tools/concepts and daily excellence | - | Manufacturing cells, process perspective |

| | | | | | | |
|---|---|---|---|---|---|---|
| | deploying the tools/concepts | | resources efficiently (efficiency) | | | |
| (Chiera et al., 2021) | Negligible in defining stakeholders value, leadership, people and learning, flexibility, modularization, continuous process flow, demand pull, stakeholders and systems integration, transparency, technology, continuous improvement | Low in defining stakeholders value, leadership, people and learning, flexibility, modularization, continuous process flow, demand pull, stakeholders and systems integration, transparency, technology, continuous improvement | Medium in defining stakeholders value, leadership, people and learning, flexibility, modularization, continuous process flow, demand pull, stakeholders and systems integration, transparency, technology, continuous improvement | High in defining stakeholders value, leadership, people and learning, flexibility, modularization, continuous process flow, demand pull, stakeholders and systems integration, transparency, technology, continuous improvement | Full in defining stakeholders value, leadership, people and learning, flexibility, modularization, continuous process flow, demand pull, stakeholders and systems integration, transparency, technology, continuous improvement | Engineer to order scenario, process perspective |

Table A.2 – Maturity levels for CE found in the literature.

| Authors | Level 0 | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | Scope |
|---|---|---|---|---|---|---|---|
| (Fatimah et al., 2020) | Traditional: limited facilities, low technology and regulations applied to meet government requirement | Common: a semi-automatic operation and focus on accessibility to the collection process | Organized: an efficient, streamlined, and effective process with total regulation compliance and some environmental | Integrated: a modern process integrated to reduce global waste, beyond regulatory compliance, high level of transparency and a culture of | Smart: globally connected through the entire system, automatic technology, big data centers and the waste treatment is | - | Waste management in cities, life cycle perspective |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | awareness of employees | environmental awareness | considered in decision making | | |
| (Golinska-dawson et al., 2021) | Very low: resource management practices are not applied or are incomplete | Low: resource management practices are applied with no formalization | Medium: resource management practices are formalized, and some actions are taken | High: resource management practices are formalized, measured, and controlled | Very high: resource management practices are formalized, measured, controlled, and continuously improved | - | Resource management in remanufacturing, life cycle perspective |
| (Bertassini et al., 2022) | Rudimentary: there are no circular strategies | Early stages: little experience and knowledge about circular strategies | Opportunist: the company believes that CE can create opportunities for cost reduction | Integrated: incorporates some circular principles in some products or services | Innovative: the company has knowledge and experience with CE | Leader: CE is in the DNA of the company | Organizations, product and life cycle perspective |
| (Uhrenholt et al., 2022) | None: only legal requirements | Basic: discussions about how and where to act to generate value with CE | Explorative: some projects developed to test organizational capabilities and prove the value of CE | Systematic: CE implementation by design | Integrative: the value of CE is aligned throughout critical supply chain | Regenerative: regenerative and restorative by intention and design | Organizations, product and life cycle perspective |
| (Kayikci et al., 2022) | Non-existent | Executed | Managed | Established | Predictable | Optimized | Supply chain, life cycle perspective |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (Aguiar & Jugend, 2022) | Inert: minimal knowledge of circular product design | Conversant: applied some principles of circularity | Applied: apply some circular strategies to some specific products | Monitored: CE is integrated with product design | Optimized: continuous improvement of circular performance in product design | - | Product design, product perspective |

## APPENDIX B – EXPERTS PROFILE WHO VALIDATED THE FIRST VERSION OF LCMM

Table B.1 – The profile of the experts who answered the survey during the validation process of the LCMM.

| | **Lean Manufacturing** | | **Circular Economy** | |
|---|---|---|---|---|
| **Years of experience** | **Experts** | **(%)** | **Experts** | **(%)** |
| 1-5 years | 1 | 9% | 3 | 38% |
| 6-10 years | 5 | 45% | 3 | 38% |
| 11-15 years | 0 | 0% | 0 | 0% |
| 16-20 years | 2 | 18% | 0 | 0% |
| More than 20 years | 3 | 27% | 2 | 25% |
| Total | 11 | 100% | 8 | 100% |

Table B.2 – Expert's profile detailed

| **Specialist** | **Country** | **Issues that have experience** | **Years of experience** |
|---|---|---|---|
| 1 | Canada | Lean Manufacturing; Lean Design; Lean Product and Process Development; Lean Office | 10 |
| 2 | Brazil | Circular Economy; Eco-design | 2,5 |
| 3 | Brazil | Lean Manufacturing; | 7 |
| 4 | Brazil | Life Cycle Assessment; Lean Manufacturing; | 9 |
| 5 | Brazil | Circular Economy; Life Cycle Assessment; Eco-design | 10 |

| | | | |
|---|---|---|---|
| 6 | Brazil | Lean Manufacturing; Lean Design; Circular Economy | 8 |
| 7 | Spain | Lean Manufacturing; | 16 |
| 8 | United Kingdom | Lean Manufacturing; Lean Design; Lean Product and Process Development; | 35 |
| 9 | United Kingdom | Lean Manufacturing; Circular Economy; Lean Product and Process Development | 3 |
| 10 | United States | Lean Manufacturing; Lean Design; Lean Product and Process Development (LPPD); Life Cycle Assessment | 10 |
| 11 | Brazil | Lean Manufacturing; Circular Economy; Eco-design; Life Cycle Assessment | 25 |
| 12 | Brazil | Lean Manufacturing | 20 |

## APPENDIX C – COMPANIES PROFILE

Table C.1 – Profile of the participating companies.

| Company / Information | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| **Sector of the economy** | Secondary | Secondary | Primary | Secondary | Primary | Secondary | Primary. | Tertiary | Secondary |
| **Size (in number of employees)** | Large | Large | Medium | Large | Small | Large | Large | Large | Large |
| **Location (Region)** | Southeast | Southeast | Southeast | Midwest | Midwest | Southeast | North | South | Southeast |
| **Nationality** | Japanese | Brazilian | Brazilian | Brazilian | Brazilian | Brazilian | North American | British | German |
| **Type of business** | National | National | National | Local | Local | National | International | International | International |
| **How long has been implementing LM? (years)** | 3 | 3 | 2 | 5 | 4 | 11 | 12 | 0 | 24 |
| **How long has been implementing CE? (years)** | 0 | 0 | 2 | 3 | 0 | 0 | 5 | 2 | 5 |

| How long has been implementing Sustainability? (years) | 10 | 3 | 2 | 3 | 8 | 11 | 8 | 51 | 10 |
|---|---|---|---|---|---|---|---|---|---|

## APPENDIX D – RECOMMENDATIONS

Table D.1 – Set of Lean-Circular recommendations by maturity level and robustness results.

| LCMM topic | Level | Robustness | Recommendation | Tools / Principles / Concepts | References |
|---|---|---|---|---|---|
| Resource efficiency strategy | Level 0 | - | Research about environmental legislation for your location and create an action plan to comply with all requirements | I-GO Assistant (https://igosolution.org/) | (IBGC, 2007) |
| | | | Implementation of basic LM with a formal structure and specialists | 5S, continuous improvement, Standard Work, Employee Training | (Hines, 2010; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 1 | - | Define a goal, define value, monitor process with indicators, develop teams to identify opportunities to have an efficient use of resources | Kaizen, visual management, Teamwork, Voice of the customer | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2, Level 3, or Level 4 | X1<0 | Define a goal, monitor process with indicators, develop teams to identify opportunities to have an efficient use of resources | Kaizen, visual management, Teamwork, Voice of the customer | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016)) |
| | Level 2 | X1>0 | Implement basic CE (recycling and renewables use), expand the efficient use of resources to your products and their end-of-life knowing their life cycle | Biomimetic, product stewardship, eco-design, life cycle thinking | (Aguiar & Jugend, 2022; Weetman, 2019) |
| | Level 3 or Level 4 | X2<0 | Implement basic CE (recycling and renewables use), expand the efficient use of resources to your products and their end-of-life knowing their life cycle | Biomimetic, product stewardship, eco-design, life cycle thinking | (Aguiar & Jugend, 2022; Weetman, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| | Level 3 | X1>0, X2>0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce the negative impact of the life cycle of your products | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X3<0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce the negative impact of the life cycle of your products | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X1>0, X2>0, X3>0 | Continuously evaluate the impact of your products, be transparent to your stakeholders, and take the waste into consideration in decision-making | Life cycle Assessment (LCA), Continuous improvement culture, Kaizen, reverse logistics, big data centers | (Fatimah et al., 2020; Kampf et al., 2005; Sacco et al., 2021; Verrier et al., 2016; Weetman, 2019) |
| Energy Management | Level 0 | - | Develop indicators of energy consumption and create a culture to reduce the consumption of energy | Visual management, Employee Training | (Fatimah et al., 2020; GRI 302, 2016; Hines, 2010; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 1 | - | Map the energy consumption in the process (gate-to-gate) and reduce the energy consumption | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2, Level 3, or Level 4 | X1<0 | Map the energy consumption in the process (gate-to-gate) and reduce the energy consumption | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2 | X1>0 | Implementation of basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |
| | Level 3 or Level 4 | X2<0 | Implement basic CE (recycling and renewable), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| | Level 3 | X1>0, X2>0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce energy consumption | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X3<0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce energy consumption | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X1>0, X2>0, X3>0 | Continuously reduce the energy consumption, share your solutions with stakeholders and be transparent | Continuous improvement culture, external learning, regenerative and restorative by intention and design | (Fatimah et al., 2020; Hines, 2010; Kampf et al., 2005; Maasouman & Demirli, 2016; Uhrenholt et al., 2022) |
| Water and Wastewater Management | Level 0 | - | Develop indicators of water consumption and wastewater, and create a culture to reduce the consumption of water | Visual management, Employee Training | (Fatimah et al., 2020; GRI 303, 2018; Hines, 2010; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 1 | - | Map the water consumption and wastewater in the process (gate-to-gate) and reduce the water consumption | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2, Level 3, or Level 4 | X1<0 | Map the water consumption and wastewater in the process (gate-to-gate) and reduce the water consumption | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2 | X1>0 | Implement basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |
| | Level 3 or Level 4 | X2<0 | Implementation of basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| | Level 3 | X1>0, X2>0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce water consumption | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X3<0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuous reduce water consumption | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X1>0, X2>0, X3>0 | Continuously reduce the water consumption, share your solutions with stakeholders and be transparent | Continuous improvement culture, external learning, regenerative and restorative by intention and design | (Fatimah et al., 2020; Hines, 2010; Kampf et al., 2005; Maasouman & Demirli, 2016; Uhrenholt et al., 2022) |
| Materials and Solid Waste Management | Level 0 | - | Develop indicators of material consumption and solid waste, and create a culture to reduce the consumption of material | Visual management, Employee Training | (Fatimah et al., 2020; GRI 301, 2016; Hines, 2010; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 1 | - | Map the material consumption and solid waste in the process (gate-to-gate) and reduce the material consumption | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2, Level 3, or Level 4 | X1<0 | Map the material consumption and solid waste in the process (gate-to-gate) and reduce the material consumption | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2 | X1>0 | Implement basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |
| | Level 3 or Level 4 | X2<0 | Implement of basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| | Level 3 | X1>0, X2>0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce material consumption | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X3<0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce material consumption | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X1>0, X2>0, X3>0 | Continuously reduce the material consumption, share your solutions with stakeholders and be transparent | Continuous improvement culture, external learning, regenerative and restorative by intention and design | (Fatimah et al., 2020; Hines, 2010; Kampf et al., 2005; Maasouman & Demirli, 2016; Uhrenholt et al., 2022) |
| Chemicals and Emissions Management | Level 0 | - | Develop indicators of consumption and emissions of chemicals, and create a culture to reduce the consumption of chemicals | Visual management, Employee Training | (Fatimah et al., 2020; GRI 305, 2016; Hines, 2010; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 1 | - | Map the consumption and emissions of chemicals in the process (gate-to-gate) and reduce the consumption and emission of chemicals | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2, Level 3, or Level 4 | X1<0 | Map the consumption and emission of chemicals in the process (gate-to-gate) and reduce the consumption and emission of chemicals | Value stream mapping (VSM), Kaizen, continuous improvement, Single minute exchange die (SMED), Total productive maintenance (TPM), Waste elimination programs | (Hines, 2010; Kampf et al., 2005; Rother & Shook, 2003; Thekkoote, 2022; Verrier et al., 2016) |
| | Level 2 | X1>0 | Implement basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |
| | Level 3 or Level 4 | X2<0 | Implement basic CE (recycling and renewables use), research alternatives to the opportunities mapped | Waste elimination programs, benchmarking, 9Rs | (Maasouman & Demirli, 2016; Weetman, 2019) |

| | | | | | |
|---|---|---|---|---|---|
| | Level 3 | X1>0, X2>0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce the consumption and emission of chemicals | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X3<0 | Assess the life cycle of your products, disseminate it to your stakeholders, and create action plans to continuously reduce the consumption and emission of chemicals | Life Cycle Management (LCM) system and/or Life cycle Assessment (LCA), industrial symbiosis, 9Rs, Environmental Assessment of Suppliers | (Ellen MacArthur Fundation, 2013; GRI 308, 2016; Oliveira Fontenelle & Sagawa, 2021; Uhrenholt et al., 2022; Weetman, 2019) |
| | Level 4 | X1>0, X2>0, X3>0 | Continuously reduce the consumption and emission of chemicals, share your solutions with stakeholders and be transparent | Continuous improvement culture, external learning, regenerative and restorative by intention and design | (Fatimah et al., 2020; Hines, 2010; Kampf et al., 2005; Maasouman & Demirli, 2016; Uhrenholt et al., 2022) |

**REFERENCES FROM SUPPLEMENTARY MATERIAL I**


Aguiar, M. F., & Jugend, D. (2022). Circular product design maturity matrix: A guideline to evaluate new product development in light of the circular economy transition. *Journal of Cleaner Production*, 132732. https://doi.org/10.1016/j.jclepro.2022.132732

Bertassini, A. C., Calache, L. D. D. R., Carpinetti, L. C. R., Ometto, A. R., & Gerolamo, M. C. (2022). CE-oriented culture readiness: An assessment approach based on maturity models and fuzzy set theories. *Sustainable Production and Consumption*, *31*, 615–629. https://doi.org/10.1016/j.spc.2022.03.018

Chiera, M., Lupi, F., Rossi, A., & Lanzetta, M. (2021). Lean maturity assessment in eto scenario. *Applied Sciences (Switzerland)*, *11*(9). https://doi.org/10.3390/app11093833

Ellen MacArthur Fundation. (2013). *Towards the Circular Economy: Economic and business rationale for an accelerated transition*.

Fatimah, Y. A., Govindan, K., Murniningsih, R., & Setiawan, A. (2020). Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *Journal of Cleaner Production*, *269*. https://doi.org/10.1016/j.jclepro.2020.122263

Golinska-dawson, P., Werner-lewandowska, K., & Kosacka-olejnik, M. (2021). Responsible resource management in remanufactur-ing—framework for qualitative assessment in small and medium-sized enterprises. *Resources*, *10*(2), 1–17. https://doi.org/10.3390/resources10020019

GRI 301. (2016). *GRI 301 Materials*.

GRI 302. (2016). *GRI 302 Energy*.

GRI 303. (2018). *GRI 303 Water and effluents*.

GRI 305. (2016). *GRI 305 Emissions*.

GRI 308. (2016). *GRI 308 Supplier environmental assessment*.

Hines, P. (2010). How to create and sustain a lean culture. *Development and Learning in Organizations: An International Journal*, *24*(6). https://doi.org/10.1108/dlo.2010.08124fad.007

IBGC, I. B. de G. C. (2007). *Guia de Sustentabilidade para as Empresas*. www.ibgc.org.br.

Jørgensen, F., Matthiesen, R. V., Nielsen, J., & Johansen, J. (2007). Lean Maturity, Lean Sustainability. *Advances in Production Management Systems*, 371–378.

Kampf, S., Seillière, E.-A., Bernard, D., Blanc, C., Delabrière, Y., Fourtou, J.-R., Hermelin, P., Jalabert, M., Laskawy, P., Montbrial, T. De, Van Ommeren, R., Ozan, T., Roger, B., Hessler, P., Roulet, M., & Unwin, G. (2005). *Annual Report Capgemini*.

Kayikci, Y., Kazancoglu, Y., Gozacan-Chase, N., Lafci, C., & Batista, L. (2022). Assessing smart circular supply chain readiness and maturity level of small and medium-sized enterprises. *Journal of Business Research*, *149*, 375–392. https://doi.org/10.1016/j.jbusres.2022.05.042

Maasouman, M. A., & Demirli, K. (2016). Development of a lean maturity model for operational level planning. *International Journal of Advanced Manufacturing Technology*, *83*(5–8), 1171–1188. https://doi.org/10.1007/s00170-015-7513-4

Nesensohn, C., Bryde, D. J., & Pasquire, C. (2016). A Measurement Model for Lean Construction Maturity. *Lean Construction Journal*, 1–9. http://researchonline.ljmu.ac.uk/

Oliveira Fontenelle, A., & Sagawa, J. K. (2021). The alignment between management accounting and lean manufacturing: rhetoric and reality. *Journal of Business and Industrial Marketing*, *36*(8), 1322–1343. https://doi.org/10.1108/JBIM-04-2020-0216

Rother, M., & Shook, john. (2003). *APRENDENDO A ENXERGAR: MAPEANDO O FLUXO DE VALOR PARA AGREGAR VALOR E ELIMINAR O DESPERDíCIO*.

Sacco, P., Vinante, C., Borgianni, Y., & Orzes, G. (2021). Circular economy at the firm level: A new tool for assessing maturity and circularity. *Sustainability (Switzerland)*, *13*(9). https://doi.org/10.3390/su13095288

Thekkoote, R. (2022). A framework for the integration of lean, green and sustainability practices for operation performance in South African SMEs. *International Journal of Sustainable Engineering*, *15*(1), 46–58. https://doi.org/10.1080/19397038.2022.2042619

Uhrenholt, J. N., Kristensen, J. H., Rincón, M. C., Adamsen, S., Jensen, S. F., & Waehrens, B. V. (2022). Maturity Model as a Driver for Circular Economy Transformation. *Sustainability (Switzerland)*, *14*(12). https://doi.org/10.3390/su14127483

Verrier, B., Rose, B., & Caillaud, E. (2016). Lean and Green strategy: The Lean and Green House and maturity deployment model. *Journal of Cleaner Production*, *116*, 150–156. https://doi.org/10.1016/j.jclepro.2015.12.022

Weetman, C. (2019). *Economia Circular: conceitos e estratégias para fazer negócios de forma mais inteligente, sustentável e lucrativa* (Autêntica Cusiness, Ed.; 1st ed.).

# 4. FINAL CONSIDERATIONS

This research aimed to study the integration of LM and CE, and how we could assess companies' maturity in terms of their processes, products, and life cycles to support decision-making towards the development of lean-circular companies. This first step was the evaluation of the present literature about such integration through a systematic literature review on LM and CE. Then, the LCMM was developed and applied in Brazilian companies as case studies to test the self-assessment maturity model.

LM has a focus on the reduction of waste and CE on the implementation of circular flows. About the integration of these two concepts, there are more convergent than divergent topics because LM and CE both seek following sustainability (economic and environmental). LM aims at reducing the consumption of resources such energy, water, materials, and chemicals; and CE develops circular flows, reducing negative impacts on the environmental.

The current literature about lean-circular integration presents the VSM as the main LM tool adopted to map relevant flows in the shop-floor area, while the technical cycle is the focus explored by CE studies. Hence, to the best of the authors' knowledge, there is no papers studying on how a company can integrate the concepts of LM and CE and move towards a more sustainable business by developing lean-circular flows.

To cover this gap a self-assessment model called Lean Circular Maturity Model (LCMM), was proposed based on MM and the stages from MCDA. The self-assessment model was applied in nine companies located in Brazil and the results showed that companies are looking for cleaner alternatives before identifying lean-circular opportunities to improve, which can cause errors in the planning and hierarchization/prioritization of actions of improvement. Also, there is a lack of training and awareness of all employees regarding the efficient use of resources (materials, energy, water, chemicals, waste) and a lack of actions to manage the life cycle of products in the entire value chain.

The LCMM is easy to apply and help decision-makers to have a clean vision of where they are now at the lean-circular scale and what they need to do to become leaner and more circular. To the best of the authors' knowledge, this was the first time that a self-assessment measure was designed for the integration of LM and CE for application in the levels of a company process, product, and/or its life cycle.

This research is limited to evaluating the economic and environmental perspectives, excluding the evaluation of social factors. Also, the application of the LCMM in large companies was done with just one employee and to have a more systematic vision about the process, product, and in life cycle thinking, more people from different areas should be interviewed on such cases.

Future research opportunities include the improvement of the self-assessment considering social aspects and creating a digital platform for easy use of the developed self-assessment LCMM.

## APPENDIX II – CO-AUTHORS OF CHAPTER 2

Table 16 – Co-authors of chapter 2

| Co-author | Contribution | Signature |
|---|---|---|
| Jayson Wilson Barretti | Text writing; Validation of results | Jayson Wilson Barretti<br>gov.br Documento assinado digitalmente<br>JAYSON WILSON BARRETTI<br>Data: 21/02/2023 21:17:29-0300<br>Verifique em https://verificador.iti.br |
| Ricardo Coser Mergulhão | Methodology | gov.br Documento assinado digitalmente<br>RICARDO COSER MERGULHAO<br>Data: 25/02/2023 10:47:46-0300<br>Verifique em https://verificador.iti.br |
| Diogo Aparecido Lopes Silva | Supervision of activities; Results analysis; Validation of results; Text writing | Diogo Aparecido Lopes Silva<br>gov.br Documento assinado digitalmente<br>DIOGO APARECIDO LOPES SILVA<br>Data: 21/02/2023 10:25:29-0300<br>Verifique em https://verificador.iti.br |

## APPENDIX III – CO-AUTHORS OF CHAPTER 3

Table 17 - Co-authors of chapter 3

| Co-author | Contribution | Signature |
|---|---|---|
| Ricardo Coser Mergulhão | Results analysis; Text writing | gov.br Documento assinado digitalmente<br>RICARDO COSER MERGULHAO<br>Data: 25/02/2023 10:47:46-0300<br>Verifique em https://verificador.iti.br |
| José Geraldo Vidal Vieira | Methodology; Text writing | |
| Andrea Brasco Pampanelli | Data collect; Text writing | DocuSigned by:<br>1C6B56008C6B4DB... |
| Rodrigo Salvador | Validation of results; Text writing | Rodrigo Salvador |
| Diogo Aparecido Lopes Silva | Supervision of activities; Results analysis; Validation of results; Text writing | gov.br Documento assinado digitalmente<br>DIOGO APARECIDO LOPES SILVA<br>Data: 21/02/2023 10:25:29-0300<br>Verifique em https://verificador.iti.br<br>Diogo Aparecido Lopes Silva |