Waste Management 173 (2024) 172–183

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Lean-circular maturity model (LCMM) for companies' self-assessment in terms of process, product and life cycle thinking

Marina Hernandes de Paula e Silva [a], Ricardo Coser Mergulhão [b], José Geraldo Vidal Vieira [b], Andrea Brasco Pampanelli [c], Rodrigo Salvador [d], Diogo Aparecido Lopes Silva [a,*]

[a] Federal University of Sao Carlos (UFSCar), Department of Production Engineering, Research Group on Sustainability Engineering (Engs Group), João Leme dos Santos Road km 110, Sorocaba, Brazil
[b] Federal University of Sao Carlos (UFSCar), Department of Production Engineering, João Leme dos Santos Road km 110, Sorocaba, Brazil
[c] Federal University of Rio Grande do Sul (UFRGS), PPGE3M Master and PhD, Av. Bento Gonçalves, 9500, Porto Alegre, Brazil
[d] Technical University of Denmark (DTU), Department of Engineering Technology and Didactics, Lautrupvang 15, Building Ballerup / Room E2.12, DK-2750 Ballerup, Denmark

ARTICLE INFO

Keywords:
Lean management
Cradle-to-cradle
Sustainability
Maturity level
Circularity

ABSTRACT

Rapidly diagnosing the status of resource efficiency and waste generation throughout the entire value chain is considered one of the key future advancements towards achieving more sustainable production. This study aimed to develop and implement a self-assessment tool to assist companies in decision-making processes for establishing circular flows based on the principles of Lean Manufacturing (LM) and Circular Economy (CE). The self-assessment tool employed a maturity model comprising several stages, which were designed through a combination of design science research and scenario planning. The Lean-Circular Maturity Model (LCMM) consisted of maturity levels ranging from 0 to 4, assessing strategies such as Resource Efficiency, Energy Management, Water and Wastewater Management, Materials and Solid Waste Management, and Chemicals and Emissions Management. The model was applied to nine companies varying in sector, size, region, and nationality. Their engagement in LM, and CE, differed, as did their strategy maturity metrics. Primary sector companies showed higher maturity in water-waste and chemical-emissions management. Larger enterprises focused on these strategies, with nuances based on region. The main findings indicated that 66% of the companies sought cleaner alternatives prior to mapping their production processes, which could lead to errors in planning and prioritizing improvement actions. Furthermore, 61% of the companies lacked sufficient training and employee awareness regarding the efficient utilization of resources. The absence of comprehensive actions to manage the life cycle of products throughout the value chain emerged as the primary barrier identified. To address these gaps, the LCMM offers a set of tailored recommendations for each company to enhance processes, products, and the value chain based on the final score obtained from utilizing the LCMM self-assessment tool.

1. Introduction

Lean Manufacturing (LM) is widely recognized as an operational mindset aimed at minimizing waste and enhancing production quality (Kurdve & Bellgran, 2021). Circular Economy (CE) seeks to keep the utility of the resources, eliminating waste in product design instead in final disposal (Weetman, 2019). Studies have demonstrated a positive correlation between LM and improvements in companies' environmental performance (de Oliveira Rezende et al., 2022, Salvador et al., 2021). Furthermore, recent research has also highlighted the beneficial association of LM principles with CE applications (Lim et al., 2022). This connection arises from LM's ability to reduce water, energy, and raw material consumption within a company level (De Paula e Silva et al., 2022a).

The integration of LM and CE provides a comprehensive approach, encompassing economic and environmental sustainability across three key areas: process, product, and life cycle thinking in companies (Schmitt et al., 2021), ultimately fostering the establishment of circular flows (Kalemkerian et al., 2022). Then, LM serves as an initial step towards waste reduction, aligning with the core objectives of CE's 10Rs

* Corresponding author.
E-mail address: diogo.apls@ufscar.br (D. Aparecido Lopes Silva).

https://doi.org/10.1016/j.wasman.2023.11.013
Received 9 August 2023; Received in revised form 24 October 2023; Accepted 13 November 2023

(less circular to more circular): recover and recycle applied to materials, repurpose, remanufacture, refurbish, repair and re-use to extend the life cycle of a product, reduce, rethink, and refuse to a smarter product use and manufacture (Shevchenko et al., 2023).

Companies are facing the challenge of making informed decisions and evaluating their advancements without a clear path towards circular flows (De Oliveira et al., 2021). To address this need, Maturity Models (MM) prove to be valuable as they provide a structured framework to assist companies in enhancing their practices and decision-making overtime (de Souza et al. (2021)). By adopting such models, companies can effectively monitor and report their progress (Asdecker & Felch, 2018).

However, the current literature lacks a clear diagnosis or a comprehensive guide for advancing the integration of LM and CE based on MM (De Paula e Silva et al., 2022a). On one hand, previous studies have established maturity levels for various sectors, including construction and industry to assess LM maturity within organizations (Hines, 2010; Maasouman & Demirli, 2016; Nesensohn et al., 2016)., On the other hand, no LM studies have incorporated aspects of environmental efficiency/performance, a life cycle perspective, or CE principles into their MM assessments (Chiera et al., 2021; Maasouman & Demirli, 2016; Verrier et al., 2016; Nesensohn et al., 2016; Hines, 2010; Jørgensen et al., 2007). Regarding the literature about MM for CE, none presented the integration with LM yet (Aguiar & Jugend, 2022; Kayikci et al., 2022; Uhrenholt et al., 2022; Bertassini et al., 2022; Golinska-dawson et al., 2021; Fatimah et al., 2020).

To the best of the authors' knowledge, no previous study has specifically addressed the assessment of integrating LM and CE to develop lean-circular companies using MM. Furthermore, existing MM found in the literature often lack a self-assessment tool that can effectively guide decision-makers and companies towards achieving economic and environmental efficiency from LM and CE (Urbinati et al., 2019). In light of this context, the primary objective of this study is to provide a solution to the following question: "How can we assess the maturity of LM and CE integration in companies to facilitate economic and environmental improvements, ultimately leading to the establishment of lean-circular companies?" To address this question, the researchers developed a novel MM known as the Lean-Circular Maturity Model (LCMM). The development process involved an exploratory literature review and the incorporation of stages from a multicriteria approach, combining scenario planning with Multi-Criteria Decision Analysis (MCDA). Subsequently, the LCMM was practically applied in a set of different companies.

Finally, this study provides a multidisciplinary theoretical contribution since it combines MM, LM and CE research topics in a MCDA approach.

2. Literature review

This section offers insights from an exploratory literature review on LM and CE, conducted by searching the SCOPUS, Web of Science, and Scholar Google databases using the keywords "lean manufacturing" and "circular economy." To enhance the literature review of MM in LM and CE, additional keywords such as "maturity model" and "maturity assessment" were included in the search criteria.

2.1. LM and CE in resource and waste management

In recent decades, traditional LM principles, which aim to create value by minimizing waste in manufacturing processes have increasingly intersected with the field of environmental sustainability, focusing on reducing pollution in the environment (Dieste et al., 2019). LM principles enable companies to identify and reduce waste generation (De Paula e Silva et al., 2022a). Positive outcomes in both environmental and economic performance have been observed when applying LM with an environmental sustainability focus. For instance, Caldera et al. (2019) found these effects in small and medium-sized enterprises (SMEs) in the secondary sector, while Dües et al. (2013), Inman & Green (2018), and Pampanelli et al. (2014) reported comparable outcomes in production systems, including medium and large-sized companies.

One of the prominent LM principles used to mitigate environmental impacts is the Value Stream Mapping (VSM), which remains the most widely employed tool today (De Paula e Silva et al., 2022a). VSM entails mapping the current state using specific indicators to illustrate the flows of information and materials in a production system, followed by developing a future state map to optimize processes (Rother & John, 2003; Oliveira Rezende et al., 2022). The incorporation of environmental indicators further enhances VSM's effectiveness (Baysan et al., 2019; de Oliveira Rezende et al., 2022).

On one hand, the integration of LM with environmental performance issues has its limitations as it mainly focuses on process-level efforts. In other words, the scope remains limited to the company's internal operations, lacking a comprehensive circular perspective on the entire process, product, and life cycle (Leme Junior et al., 2018; Schmitt et al., 2021). On the other hand, the literature on CE emphasizes reducing emissions and resource consumption throughout the entire product life cycle (Aguiar & Jugend, 2022; De Paula e Silva et al., 2022a; Mainardis et al., 2022).

Indeed, the integration of LM and CE can pave the way for a holistic vision of the company, leading to improved economic and environmental performance (De Paula e Silva et al., 2022a). However, due to the recent emergence of this concept, only a limited number of studies have explored this integration, resulting in a gap in the literature, particularly concerning the application of this integration at a life cycle thinking.

The integration of LM and CE yields significant positive effects, notably reducing waste in manufacturing processes and creating value through waste in products and processes (Kalemkerian et al., 2022; Lim et al., 2022; Schmitt et al., 2021). Additionally, LM principles benefit reverse logistics and eco-design by enhancing efficiency, productivity, flexibility, and reducing lead time and complexity (Ciliberto et al., 2021; Schmitt et al., 2021). Incorporating the principles of "reuse" and "remanufacture" can further boost economic performance by generating new business opportunities for the company (Leme Junior et al., 2018; Schmitt et al., 2021).

Despite these benefits, it is noteworthy that no previous study has explored the assessment of the integration of LM and CE from a comprehensive perspective covering a company's process, product, and life cycle. This assessment is essential as it can aid decision-makers in developing a lean and circular company, transitioning from a simpler process to a more intricate value chain while incorporating a life cycle thinking perspective. In this context, the use of MM theory could play a pivotal role in facilitating the development of this assessment.

2.2. Maturity models in LM and CE

The concept MM can be traced back to 1979 with Philip B. Crosby's introduction of the Quality Management Maturity Grid (Crosby, 1980). However, the Capability Maturity Model Integration (CMMI) developed by the Software Engineering Institute (Chrissis (2011)) has become the most recognized and widely used method across various sectors. MM holds significant relevance as they provide valuable support to decision-makers in achieving their objectives by offering insights into their current position and identifying the next steps (Bertassini et al., 2022). Through the evaluation of a set of criteria across different levels, MM establishes a roadmap for improving specific areas (Król & Zdonek, 2020). Furthermore, MM facilitates a comprehensive analysis of a company's current state and highlight areas that require attention (Arekrans et al., 2021).

Previous studies have indeed made efforts to develop levels and assessment tools to evaluate the maturity of LM across various sectors and companies. Table A.1 in Supplementary Material I provides a comprehensive comparison of the main findings from the literature. Based on the exploratory literature review, it is evident that the current

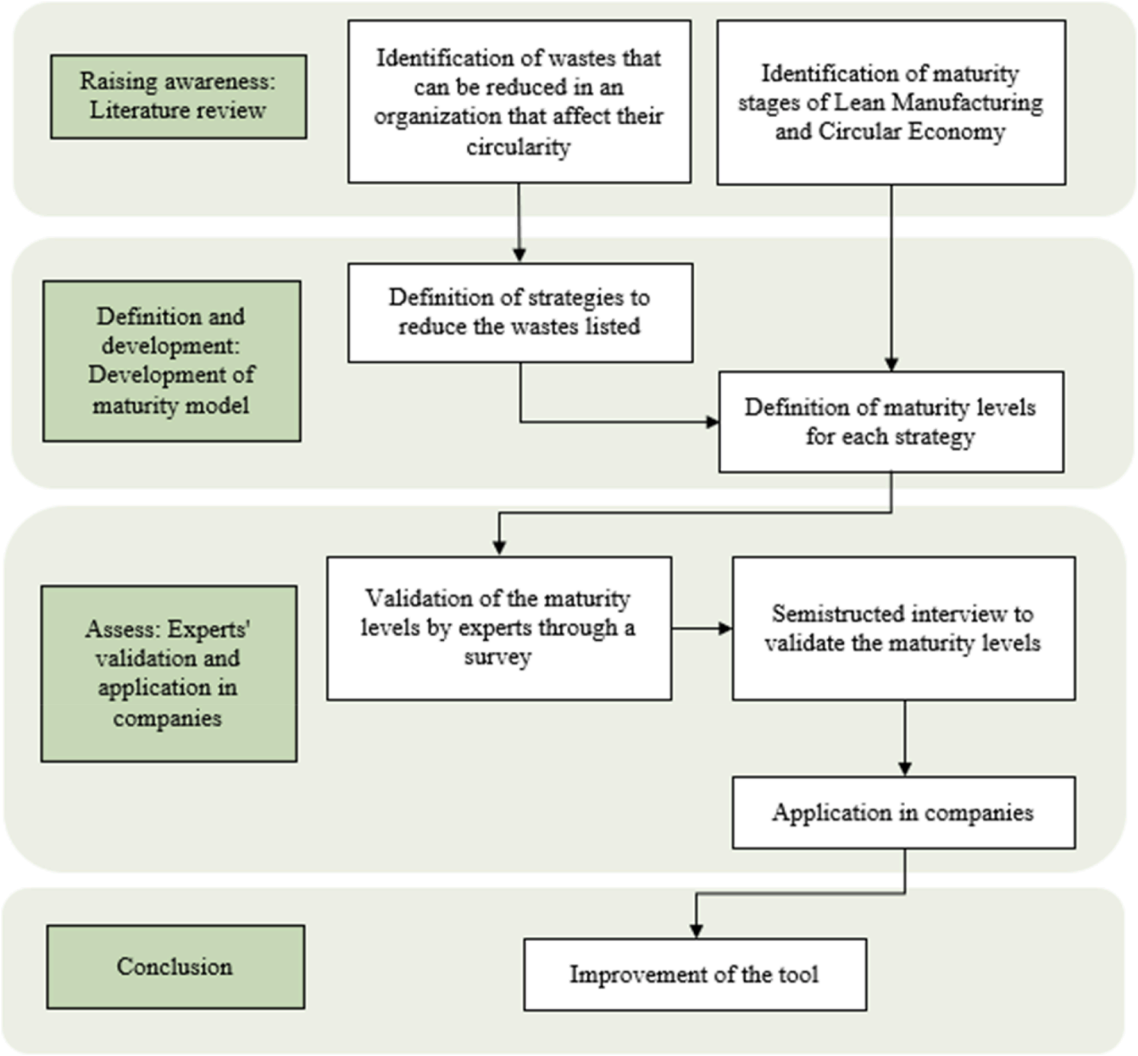

Fig. 1. Structure of methodology.

literature on MM concerning LM primarily adopts a process perspective to measure the maturity of LM in companies. Notably, five out of six studies reveal that the highest level of maturity is characterized by achieving a continuous improvement culture at companies (Chiera et al., 2021; Hines, 2010; Maasouman & Demirli, 2016; Nesensohn et al., 2016; Verrier et al., 2016). Furthermore, the six studies listed in Table A.1 have exclusively focused on developing MM for sectors within the secondary sector, specifically manufacturing industries (Chiera et al., 2021; Hines, 2010; Jørgensen et al., 2007; Maasouman & Demirli, 2016; Verrier et al., 2016) and construction processes (Nesensohn et al., 2016).

In the context of CE, several studies have dedicated efforts to develop levels and assessment tools to evaluate the maturity of CE within companies. For a comprehensive overview of these maturity levels, Table A.2 in Supplementary Material I presents a comparison of findings from the literature. Among the six studies listed, five of them utilized a life cycle perspective to measure the maturity of CE within a company (Bertassini et al., 2022; Fatimah et al., 2020; Golinska-dawson et al., 2021; Kayikci et al., 2022; Uhrenholt et al., 2022). However, Aguiar & Jugend (2022) adopted a product perspective to evaluate the maturity of CE specifically in product design.

It is essential to highlight that Golinska-Dawson et al. (2021) centered their study on the secondary sector, specifically evaluating the maturity in resources management at companies. Conversely, Fatimah et al. (2020) conducted an assessment of CE maturity in waste management practices. However, a key limitation of these papers lies in the fact that CE was not integrated with LM. As a result, they did not explore the potential benefits of incorporating LM principles as a pathway to create more value or synergy in the development of lean-circular production systems.

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 Fig. 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.

3.1. Development and validation of the LCMM

We adapted the stages proposed by Goodwin & Wright (2005) and Ram et al. (2011) in the construction of LCMM. The structure of the LCMM comprises two main macro steps: (i) the development and validation of the LCMM, and (ii) its application for assessing the maturity level of companies.

In step (i), an exploratory literature review was conducted, as described in section 2. During this process, maturity levels were formulated, and the LCMM was subsequently validated by experts in the

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

Expert.	Country	Position	LM Experience (years)	CE Experience (years)
a	Canada	Engineer	10	0
b	Brazil	PhD student	0	2.5
c	Brazil	–	7	0
d	Brazil	Professor	9	9
e	Brazil	Consultant	0	10
f	Brazil	Consultant	8	8
g	Spain	Professor	16	0
h	United Kingdom	Professor	35	0
i	United Kingdom	PhD Student	3	3
j	USA	Professor	10	10
k	Brazil	Consultant	25	25
l	Brazil	Professor	20	0

field of interest. A total of 57 experts, including LM and CE researchers and consultants, were selected and contacted via email to participate in a survey (see Appendix B of Supplementary Material I) aimed at validating the developed LCMM. The use of email was strategic to facilitate a straightforward and accessible means for experts to engage with and respond to the survey, ensuring optimal convenience and encouraging sincere and uninhibited feedback due to the allowance of anonymous responses. Out of the total, 12 experts responded to the survey, representing 21 % of the participants, in which 5 of them were LM and CE experts, 5 LM experts and 2 CE experts. These experts were from various institutions (58 % from academia and 33 % from private companies), including 7 from Brazil, 2 from the United Kingdom, 1 from the USA, 1 from Canada and 1 from Spain. Table 1 provides further information about the profile of the participating experts. Expert feedback was rigorously analyzed quantitatively for trends and qualitatively for themes. Discrepant feedback triggered further literature review and possible expert re-consultation to understand differing viewpoints, ensuring the LCMM development considered all expert insights comprehensively and accurately. Following the analysis of the survey feedback, a second version of the LCMM was proposed.

To validate the second version of the LCMM, we conducted semi-structured interviews (see Appendix B of Supplementary Material I) with the experts who answered the survey in Table 1. These interviews were conducted online, and the experts were asked to evaluate the LCMM and provide valuable suggestions. Based on the insights gathered during the validation process, we proceeded to develop a third version of the LCMM. In this updated version, we included Level 0 within the model and also streamlined the self-assessment questionnaire. The final version of the LCMM is now available as Supplementary Material II.

3.2. Application and recommendations

We employed a semi-structured questionnaire and conducted interviews with a total of 9 companies to assess their performance concerning each strategy/maturity level combination, specifically evaluating their maturity in both LM and CE. The selection of these companies was based on exploratory research, and we extended invitations to them to participate in the interview process. To ensure ethical compliance, the interview procedure was thoroughly reviewed and approved by the ethical committee (CONEP – Brazil), with the process number 5526334. This step was crucial in safeguarding the rights and interests of the participating companies and ensuring that all ethical considerations were adequately addressed throughout the research process.

The interview process adhered to the following steps:

Initial presentation: We provided an introductory overview of the study, including its objectives and the outlined steps.

Company information collection: Pertinent information about the participating companies was gathered. Information available in Table C.1 about companies' size, geographical location, and LM and CE initiatives experience.

Respondent information collection: We collected relevant details about the respondents participating in the interview. Information already provided on Table 1.

Maturity assessment based on the developed model: The maturity of each company, concerning LM and CE, was assessed using the model we had developed.

Feedback on the LCMM and its application: Participants were encouraged to provide feedback and insights on the LCMM and its practical application. Information can be seen in Appendix B from the Supplementary Material I.

After conducting the interviews, we proceeded to analyze the LCMM application results using both qualitative and quantitative methods, as detailed in Section 4. In addition, a crucial aspect involved measuring the level-by-level robustness of each company. This analysis provided valuable complementary insights to the list of tailored Lean-Circular recommendations, specifically focusing on advancements in resource efficiency topics within a life cycle thinking perspective (refer to Appendix C in Supplementary Material I for more details).

To provide further clarity, if the advancement towards a circular flow within a lean-circular process, product, and life cycle thinking demonstrated robustness, the score for Level 1 would surpass that of Level 2. Likewise, Level 2 would achieve a higher score than Level 3, and subsequently, Level 3 would surpass Level 4 in terms of scoring. The calculation of this metric followed the specified steps outlined in the study.

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

$$X_1 = scoreLevel1 - scoreLevel2 \quad (1)$$

$$X_2 = scoreLevel2 - scoreLevel3 \quad (2)$$

$$X_3 = scoreLevel3 - scoreLevel4 \quad (3)$$

b) Sum the negative values.

The lower the sum in item b, the lower the final company robustness. Therefore, the set of Lean-Circular recommendations by using the LCMM is given by maturity level and robustness results to support companies in becoming more lean-circular.

4. Results

4.1. LCMM development and validation

The primary objective of using the LCMM self-assessment tool is "to assess the integration of LM and CE in companies, aiming to achieve lean-circular flows with a comprehensive perspective encompassing process, product, and life cycle considerations". This integration of LM and CE is characterized by a key focus on waste life cycle reduction, which consequently leads to improved economic and environmental efficiency (De Paula e Silva et al., 2022b). To effectively address this integration, three interdependent perspectives must be taken into account: process, product, and life cycle thinking, as explained by Schmitt et al. (2021). The "process" perspective entails components like sourcing, logistics, and production. The "product" perspective focuses on research and development areas. Lastly, the "life cycle thinking" perspective encompasses the environmental impact beyond the company gate, encompassing the entire product life cycle. By considering these three perspectives, companies can develop a more comprehensive

Table 2
Maturity levels developed and validated in Stage 3.

Perspective Topics	Minimum requirement Level 0	Process Level 1	Level 2	Product Level 3	Life cycle 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.

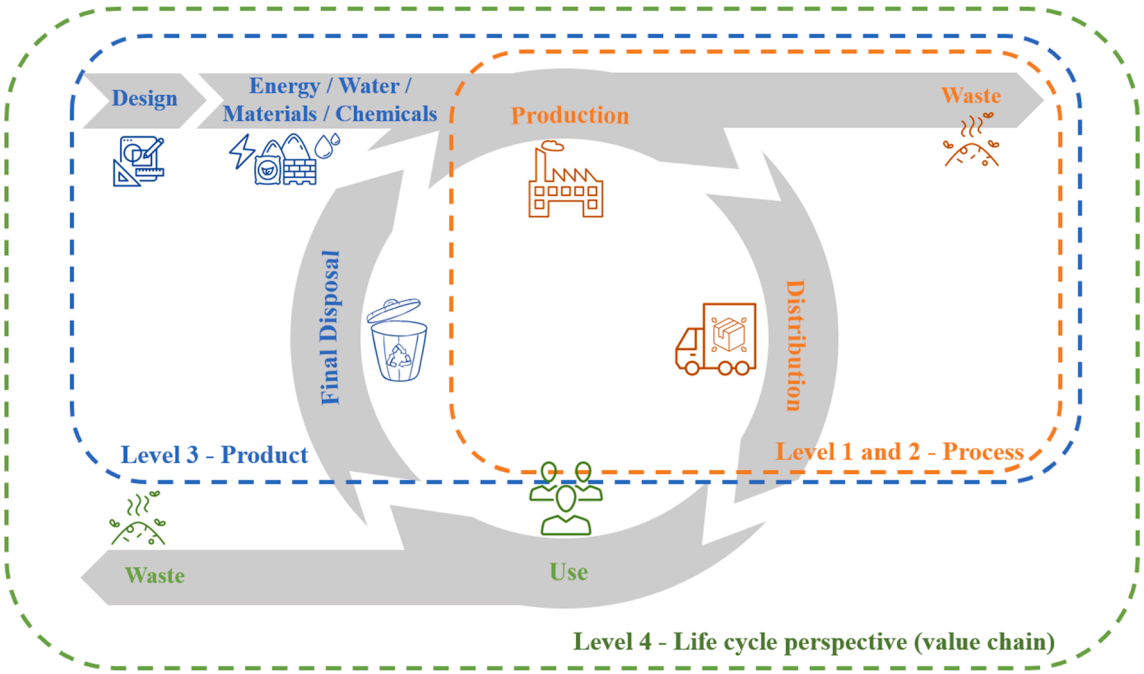

Fig. 2. Maturity levels scheme developed and validated in Stage 3 divided into the three perspectives.

approach to achieving a lean-circular production system with greater environmental and economic benefits. Supplementary material II shows the final version of the LCMM developed self-assessment tool.

The LCMM formulates strategies to align with the defined objectives. LM centers around reducing waste and enhancing value-added activities within a company (Rother & John, 2003; Leme Junior et al., 2018), while CE aims to establish circular flows for resources recovery (Weetman, 2019). Based on these principles, we assessed four key resource efficiency topics: energy, water and wastewater, materials and solid waste, and chemicals and emissions. Consequently, four strategies emerged to achieve the objectives of the LCMM: Energy Management, Water and Wastewater Management, Materials and Solid Waste Management, and Chemicals and Emissions Management. To enhance the scope for companies' application, we incorporated an additional strategy called "Resource Efficiency Strategy." This strategy was added based on the valuable input and suggestions provided by specialists (see section 3.1 again), aiming to further support companies in their pursuit of lean-circular practices and sustainable resource management.

Table 2 provides a detailed description of the developed and validated maturity levels of the LCMM, while Fig. 2 presents a visual representation of how these maturity levels are applied in practice. To create scenarios for the "Resource Efficiency General Strategy," we relied on the Brazilian Institute of Corporate Governance (IBGC., (2007)) as a reference. By doing that, we were able to devise scenarios that effectively gauge and guide companies in advancing their businesses to become more lean-circular.

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 current literature (see Tables A.1 and A.2 in Appendix A from Supplementary Material I).

In Table 2, level 0 indicates that the company has not yet implemented any principles related to LM or CE. Moving on to level 1, the company has taken significant steps towards resource efficiency by developing key performance indicators (KPIs) and conducting internal training for all employees to emphasize responsible resource usage. Effective KPIs are crucial in formulating, communicating, and implementing strategies, and engaged employees play a pivotal role in the successful execution of these strategies (Setianto & Haddud, 2016). Both LM and CE are considered in this stage, with a focus on internal resource management and training initiatives.

At level 2, the company has progressed further by implementing the VSM tool specifically at the process level to identify and reduce resource usage. VSM provides a comprehensive overview of the current state of a process, facilitating the management of improvements towards a more efficient future state (de Oliveira Rezende et al., 2022; Salvador et al., 2021). Levels 1 and 2 represent the process perspective, highlighting the company's emphasis on optimizing resource efficiency within its internal operations.

At level 3, the company demonstrates a continuous commitment to monitoring and evaluating technological alternatives aimed at minimizing the negative environmental impacts associated with both its processes and products. This approach involves integrating circularity principles that emphasize the use of circular inputs, such as recycled materials, renewable sources, and resource reduction in products and processes (Weetman, 2019). By embracing the principle of continuous improvement from LM (Leme Junior et al., 2018), sustainability is seamlessly incorporated into the company's processes (Maasouman & Demirli, 2016). Level 3 is reflective of the product perspective, wherein the company focuses on environmentally improving its products.

Advancing to level 4, the company takes a more holistic approach by expanding the value stream assessment to encompass the entire life cycle of its products, considering the entire value chain. At this level, achieving circular flows becomes a core objective, where the company's daily practices are oriented towards continuous improvement. Circular flow is attained when the company can effectively reuse, remanufacture, or recycle its products without compromising their value (Weetman, 2019). Level 4 embodies the life cycle perspective, signifying the company's commitment to sustainability and resource efficiency across its entire operations and product life cycle. This level can be considered as the main challenge for future perspectives in resource efficiency and waste management. Successfully reaching level 4 requires a paradigm shift in the company's business model and a commitment to continuous improvement in resource efficiency. Moreover, it necessitates innovation, investment in research and development, and fostering a culture of sustainability and circular thinking throughout the organization.

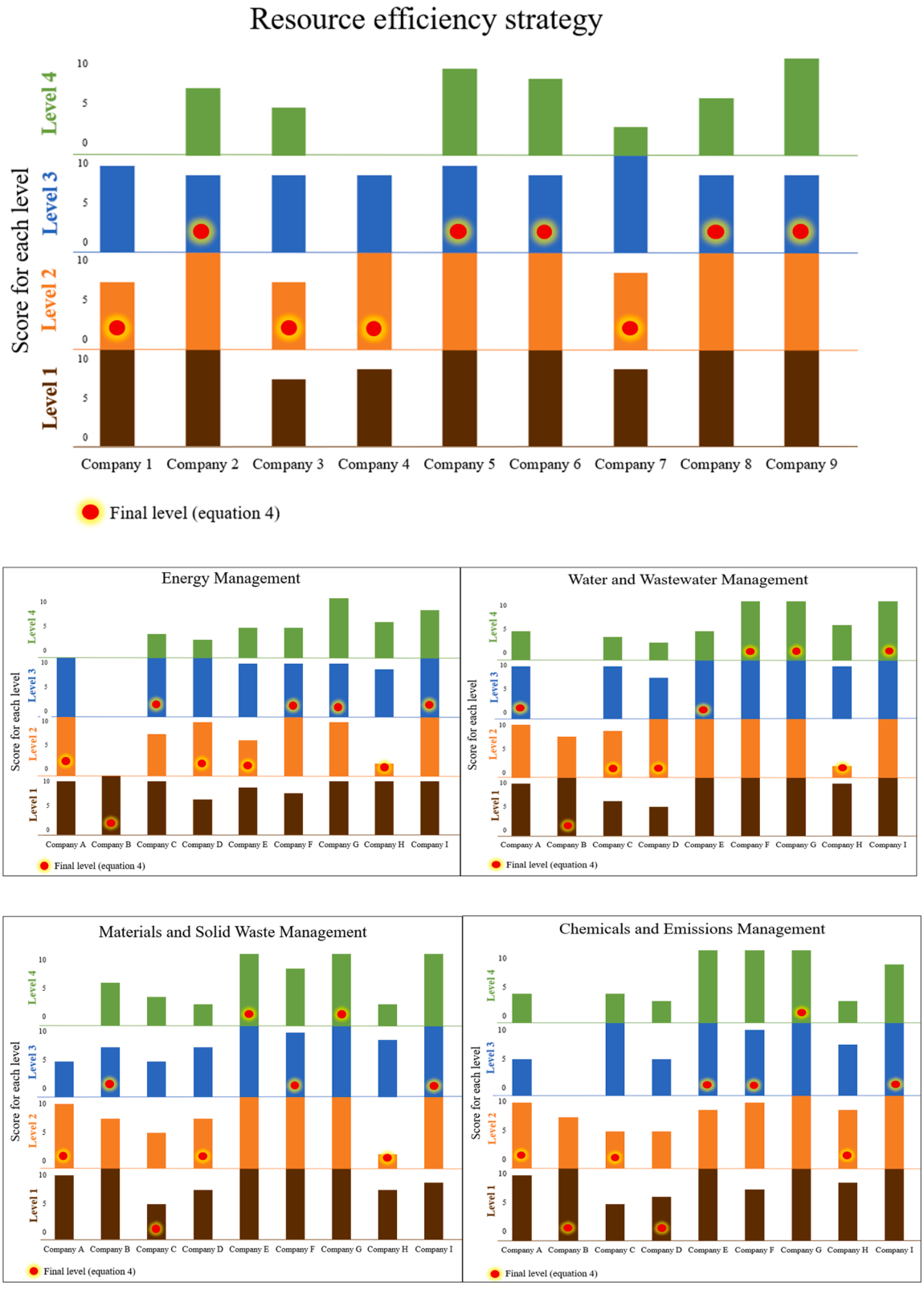

Fig. 3. Score of each company in each level for each topic of the LCMM application.

4.2. LCMM application

This step was to evaluate the company's performance in each strategy/maturity level combination.

The companies participated in a self-assessment process, where they assigned a score ranging from 0 (totally disagree) to 10 (totally agree) for each topic and maturity level statement listed in Table 2. The choice of a 0 to 10 scale was based on existing studies, which found it to be more user-friendly for interviewees (Carvalho et al., 2021). For Level 0 statements, which represent minimum requirements, if a company self-evaluated a score equal to zero, it indicated that they had met the minimum requirements for that specific topic. In such cases, the

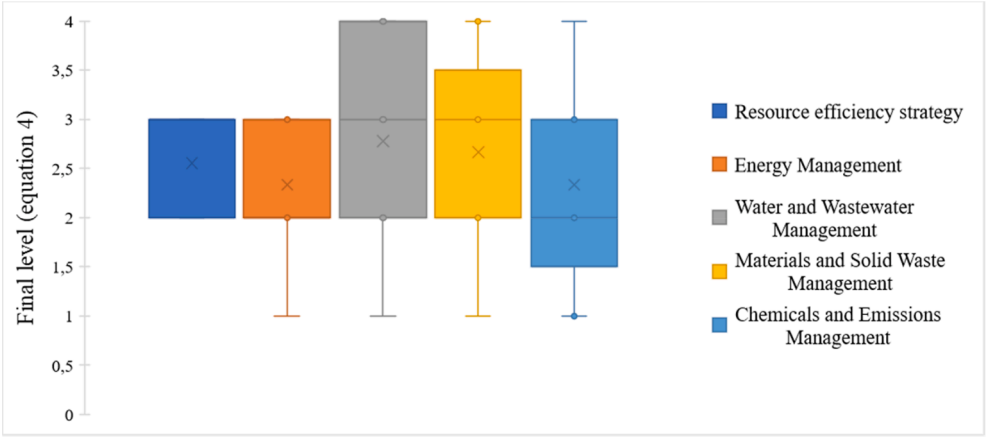

Fig. 4. Distribution of the levels for each strategy.

company would need to address any remaining related issues to that topic before proceeding further in the assessment. However, if the score for any Level 0 statement was higher than zero, it would suggest that the company had not fully met the minimum criteria and should move on to the next topic for evaluation.

After completing the self-assessment process, we used Equation (4) to calculate the final maturity level for each corresponding topic. The equation involved rounding down to no decimal places, ensuring a straightforward and concise determination of the company's maturity level in each specific area. This approach provided a clear and actionable insight into the company's overall performance and progress towards lean-circular practices and resource efficiency in a comprehensive manner.

$$Finallevel = \frac{\sum scorefromeachtopic}{10} \quad (4)$$

Nine companies from diverse sectors and sizes willingly participated in the LCMM testing. To evaluate the maturity of LM and CE implementation within these companies, interviews were conducted with individuals responsible for these areas, and they were asked to perform the assessment using the online spreadsheet tool (available in Supplementary Material II).

The outcomes of the LCMM application are illustrated in Figs. 3 and 4. These figures display the scores of each level for each company, with the final calculated maturity level highlighted, utilizing Equation (4). Through these visual representations, the companies can clearly observe their performance and progress in terms of lean-circular practices and resource efficiency. The assessment outcomes serve as valuable insights for companies to identify strengths, weaknesses, and potential areas for improvement in their sustainability and circularity efforts.

4.2.1. Resource efficiency strategy

Regarding Fig. 3, the results indicate that almost 67 % of the total interviewed companies achieved the highest scores in levels 1 and 2 for the resource efficiency general strategy, with none scoring below 7 in these levels. In level 3, 67 % of the companies provided a self-assessment score of 8, while 22 % scored 9, and only one company attained the highest score of 11 %. However, in level 4, there was a more diverse range of scores, with two companies answering with the lowest score (22 %), three companies between scores 3 and 6, four companies between scores 7 and 9, and just one company self-assessed with the highest score (11 %).

Regarding the final maturity level, companies B, E, F, H, and I reached the highest level (level 3) compared to others, and no company achieved level 4. This demonstrates that the majority of the companies were successful in achieving high maturity levels in the resource efficiency general strategy but still have room for improvement to reach the level 4. These results highlight the progress made by the companies in their efforts to integrate LM and CE principles but also underscore the ongoing journey towards achieving full circularity and sustainability in their operations.

4.2.2. Energy management

In the topic of energy management, the results from Fig. 3 show that in level 1, 55 % of the companies self-assessed with a score of 9, with only one company achieving the highest score, and none scoring below 6.

In level 2, 33 % of the companies scored 10, four companies fell between scores 6 and 9, 11 % answered with the lowest score (0), and another 11 % answered with a score of 2. Moving to level 3, 67 % of the companies achieved the highest score, while four companies were between scores 8 and 9, and only one company answered with the score of zero. Level 4 displayed a more varied distribution, with 22 % of the companies self-assessing with a score of zero, 22 % scoring 5, another 22 % scoring zero again, 11 % scoring 6, 11 % scoring 4, and the last 11 % scoring 3.

Regarding the final maturity level, companies 3, 6, 7, and 9 reached level 3, while none of the companies achieved level 4. These results indicate that the majority of companies excelled in energy management, with a substantial number achieving high maturity levels in levels 1 to 3. However, like other areas, there is still progress to be made to attain the highest level of maturity in energy management. Companies C, F, G, and I stand out as having reached the highest level compared to others.

4.2.3. Water and waste water management

According to Fig. 3, Level 1 had 55 % of the answers with a score of 10, 22 % scored 9, 11 % scored 5, and another 11 % scored 6. A similar distribution was observed in level 2, with 55 % scoring 10, 11 % scoring 9, 11 % scoring 8, 11 % scoring 7, and the remaining 11 % scoring 2.

In level 3, 44 % of the companies answered with a score of 10, 33 % scored 9, 11 % scored 7, and 11 % scored 0. In level 4, 33 % of the companies answered with the highest score, 5 companies answered between 6 and 3, and one (11 %) provided the lowest score of 0.

Regarding the final maturity level, companies F, G, and I achieved level 4, indicating their high level of maturity in water and wastewater management. Overall, the results suggest that most companies demonstrated strong performance in water and wastewater management, with several of them reaching higher levels of maturity. However, there are still some areas for improvement for some companies to further enhance their resource efficiency and circular practices in water management.

4.2.4. Materials and solid waste management

The results revealed that 44 % of the companies achieved the highest score in level 1. In level 2, 44 % of the companies excelled with a score of

Table 3
Robustness results.

LCMM topic	Robustness	Company									Total
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	
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**

10, while 22 % scored 7, 11 % scored 9, 11 % scored 5, and another 11 % scored 2.

In level 3, 33 % of the companies reached the highest score, which is consistent with the same percentage of companies that achieved level 4. Notably, only companies E and G attained some scores in level 4, indicating their higher level of maturity in materials and solid waste management compared to others.

Overall, the results indicate a positive performance in materials and solid waste management, with several companies achieving high scores in levels 1 to 3. However, there is still room for improvement in reaching level 4 for most companies. Companies E and G stand out as having achieved a higher level of maturity in this aspect compared to others.

4.2.5. Chemicals and emissions management

The results demonstrated that 44 % of the companies achieved the highest score in level 1 for materials and solid waste management. Moving to level 2, 44 % of the companies stood out with a score of 10, while 22 % scored 7, and 11 % each scored 9, 5, and 2. In level 3, 33 % of the companies reached the highest score, which is consistent with the same percentage of companies that achieved level 4. Notably, only companies E and G attained some scores in level 4.

The box plot in Fig. 4 illustrates the distribution of maturity levels for each strategy. It is evident that the water and wastewater management strategy achieved the highest final levels, while the resource efficiency general strategy displayed final levels mainly between 2 and 3. Notably, both energy management and resource efficiency general strategy did not have any companies reaching level 4, indicating room for improvement in these areas. Conversely, the lowest final levels were observed in the chemicals and emissions management category.

4.3. Comparative analysis of strategy maturity by company characteristics

The model was applied across nine distinct companies, encompassing diverse attributes in terms of sector (Primary, Secondary, Tertiary), size (Small, Medium, Large), region (Southeast, Midwest, North, South), and nationality (Japanese, Brazilian, North American, British, German). Spanning both national and international types of businesses, these companies showcased varying degrees of engagement in LM and CE. Their strategy maturity was further detailed by metrics including resource efficiency (RES), energy management (EM), water-waste management (W-WM), materials-solid waste management (M−SWM), and chemical-emissions management (C-EM) in Table C.1, as Supplementary Material I. This comprehensive table offers a structured view into the diverse strategic approaches adopted by these firms, highlighting the correlation between their core attributes and in LM and CE initiatives.

In the context of nationality, Japanese-affiliated Company A focuses on LM with 3 years of implementation and dedicates a significant 10 years to CE. Companies under Brazilian nationality, specifically B, C, D, E, and F, exhibit varied years in LM engagement (ranging from 2 to 11 years) with an increasing emphasis on CE that extends up to 11 years. North American Company G has consistently engaged in LM for 12 years. British-affiliated Company H prioritizes CE in the last few years. In contrast, German-affiliated Company I records the highest engagement in LM, extending 24 years, combined with a 5-year focus on CE.

Sector-based analysis provides further granularity. Primary sector companies, namely C, E, and G, are observed to possess elevated strategy maturity in areas such as water-waste management (W-WM) and chemical-emissions management (C-EM), primarily due to the nature of their operations which demand intensive natural resource utilization. The secondary sector, represented by companies A, B, C, E, F, and H, consistently highlights CE as an area of focus. Meanwhile, the solitary tertiary sector firm, Company H, demonstrates a uniformly balanced strategy maturity across different domains, which is indicative of its holistic approach to sustainability.

A review on Table C.1 based on the maturity of different strategies highlights a dominant emphasis on W-WM and C-EM. When correlating sector with maturity levels, primary firms (C, E, G) typically manifest heightened maturity in areas like W-WM and C-EM, which can be attributed to their operational characteristics. Secondary sector firms, including A, B, D, F, and I, not only display commitment to W-WM but also maintain a balanced engagement in resource efficiency (RES) and energy management (EM). Company H, representing the tertiary sector, maintains a well-rounded maturity level in all strategies, possibly a reflection of its broad operational footprint.

In terms of company size, larger enterprises, such as A, B, D, F, G, H, and I, predominantly emphasize W-WM and C-EM strategies. Company C, of medium size, leans towards a pronounced maturity in energy management (EM), whereas the smaller entity, Company E, underscores solid waste-materials management (M−SWM).

Regional distinctions further elucidate strategy preferences. Companies operating in the Southeast region, A, B, C, F, and I, lean significantly towards the C-EM domain. This might be attributed to the region's stringent environmental norms. In the Midwest, companies D and E maintain a balanced strategy maturity across domains. Entities in

the North and South regions, represented by G and H respectively, prioritize W-WM and C-EM, pointing towards a regionally tailored resource management approach.

It becomes evident that strategy maturity levels are intrinsically tied to unique company attributes, encompassing aspects like sector, size, and geographical positioning. These associations yield critical insights into the prioritization and application of sustainable practices, contingent on operational prerequisites and regional influences.

4.4. Robustness analysis

Finally, following the steps to calculate the robustness as presented in section 3.2, the results are shown in Table 3. Negative values are highlighted in red. Among the topics assessed, Energy Management exhibited the lowest robustness, with a sum of –22. Particularly, company number 8 had the lowest robustness score within this strategy, totaling −6.

For the Materials and Solid Waste Management, 77 % of the companies achieved a robustness score of 0, indicating the highest level of robustness. However, the overall robustness assessment for companies C and H were the lowest, summing −12 and −19, respectively. On the other hand, company B obtained the highest robustness score, summing 0. This result can be attributed to the fact that company H scored higher in Level 3 than Level 2 in 60 % of the evaluated strategies, while company B demonstrated a consistent growth pattern, with Level 1 consistently outperforming Level 2, and Level 2 outperforming Level 3.

The X2 (equation (2), calculated by subtracting Level 3 score from Level 2 score, showed the lowest robustness, summing −39. This suggests that companies were seeking sustainable alternatives before fully mapping their processes.

To a better understanding about this novelty index, the robustness index can be linked with capability. Teece et al. (1997) defines dynamic capability as the ability to address rapid changes and a high robustness index guarantees that the company has know-how to go the next step faster than a company that has a low robustness index. In other words, companies with a high level of robustness may have a high level of capability.

In light of these findings, we provided a list of recommendations to each company along with the self-assessment results to enhance their robustness. These tailored recommendations are presented in the following section.

4.5. Development of tailored 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 C.2 in Appendix C from the Supplementary Material I) following the levels we developed for the LCMM.

Upon completing the self-assessment diagnosis, each company will receive a final level and robustness index associated with each strategy. Based on the specific results for each reference situation, tailored recommendations have been developed, incorporating relevant LM and CE tools, principles, and concepts. These recommendations aim to assist companies in their journey towards becoming more lean-circular over time.

By following this set of recommendations, companies can effectively progress towards a more sustainable production approach. The provided guide and work plan offer a clear path for enhancing resource efficiency and waste management, transitioning from a process perspective to a more comprehensive life cycle thinking. Ultimately, this approach facilitates the integration of LM and CE principles, driving companies towards improved economic and environmental performance while advancing their sustainability goals.

5. Discussion

Despite the promising prospects about the integration of LM and CE, the limited literature addressing process, product and life cycle areas presents challenges in obtaining a clear vision of the path towards building circular flows using LM as a foundation. To address this gap, the LCMM introduced in this study offers companies a valuable tool for conducting self-assessments and charting a course towards adopting lean and circular processes, products, and life cycle thinking. Through this self-assessment, companies gain insights into their current performance, identify areas for improvement, and understand the necessary next steps on their journey towards sustainability. By leveraging the LCMM, companies can enhance their economic and environmental performance in a synergistic manner.

The model was applied across nine distinct companies, showcasing varying engagement in LM and CE. Their strategy maturity was clarified using metrics like resource efficiency (RES), energy management (EM), and others. In terms of nationality and sector distinctions, Company A's focus was contrasted with Brazilian companies, with various sectors highlighting different maturity levels in strategies. Strategy maturity levels tend to correlate with unique company attributes like sector, size, and geographical positioning.

Among the strategies evaluated, water and wastewater management showed the highest maturity levels, closely followed by materials and solid waste management. This observation may be attributed to the existence of robust public policies in Brazil concerning water and solid waste resources, which likely contributed to the companies' emphasis on efficient management in these areas.

However, the results in robustness index highlighted some weaknesses in energy management practices across all strategies. Companies appeared to be focusing on developing clean energy alternatives before fully mapping their energy usage, indicating a need for better understanding and optimization of energy consumption. This trend was evident in the X2 calculation, where the maturity at Level 3 exceeded that at Level 2 in all strategies.

Another area of concern was the robustness between Level 1 and Level 2, where some companies failed to implement resource efficiency training that targeted all employees. Instead, the training seemed to be limited to specific departments or employees directly involved in certain areas, such as the Continuous Improvement sector. A more comprehensive and inclusive approach to training would likely lead to more effective resource management practices.

With the LCMM results and robustness index in hand, companies can access a list of recommendations derived from relevant literature for each specific level. These recommendations offer actionable steps and best practices to guide companies in their journey towards lean and circular practices. By integrating these recommendations into their operations, companies can foster continuous improvement, optimize resource utilization, and enhance their economic and environmental performance.

Comparing our LCMM with existing maturity models in the literature (Tables A.1 and A.2), it is evident that our model fills gaps by providing a holistic approach, considering process, product, and life cycle perspectives. While several existing models in the literature, such as those by Jørgensen et al. (2007) and Hines (2010), focus mainly on the manufacturing industries from a process perspective, our model provides a more comprehensive view, including a product and life cycle perspectives, which are less studied. Similarly, while models on Circular Economy, like those by Fatimah et al. (2020) and Golinska-dawson et al. (2021), emphasize life cycle perspectives in specific areas, our LCMM provides an overarching view that incorporates diverse sectors.

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

Table 4
Comparison of the proposed MM and the other existing MMs presented in the literature.

Lean-Circular existing maturity models	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	☺	☹	☹	☹	☺	☺	☺

a replicable methodology that can be used to develop maturity models in different research areas. In addition, the robustness index is a novelty regarding MM proposals and applications. 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.

6. Final remarks

In conclusion, the LCMM serves as a valuable tool for companies to assess their maturity in various topics and identify areas for improvement. The resulting recommendations provide a roadmap for companies to advance towards greater sustainability and efficiency, aligning economic growth with environmental stewardship.

The LCMM self-assessment tool consisted of a MM developed through a set of stages from MCDA combined with scenario planning. The proposal has five maturity levels and was applied in nine companies 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.

An in-depth comparative analysis revealed that the maturity levels are intrinsically tied to company-specific attributes, emphasizing the significant impact of factors like sector, size, and regional influences on the implementation and prioritization of sustainable practices.

Compared with prior papers in this area, it can be concluded that this paper represents a significant advancement in the field of integrating LM and CE, contributing to the recent theoretical knowledge on this subject. It introduces a valuable self-assessment procedure to measure the maturity level of processes, products, and product life cycles in companies concerning LM and CE. By focusing on the secondary sector, the LCMM serves as a valuable tool to help companies gain clarity about their current state and identify strategies to enhance their lean and circular practices. To the best of the authors' knowledge, this was the first time that a LM and CE self-assessment measure was provided in terms of process, product, and from a life cycle perspective.

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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Detailed data is provided as supplementary material.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.11.013.

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. J. Clean. Prod. 365, 132732. https://doi.org/10.1016/j.jclepro.2022.132732.

J. Arekrans S. Ritzén R. Laurenti Circular Economy Transitions: The Maturity of Incumbents. *22nd CINet Conference:* 2021 *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. J. Model. Manag. 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. J. Clean. Prod. 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. Int. J. Logist. Manag. 32 (1), 118–137. https://doi.org/10.1108/IJLM-10-2019-0284.

Cherrafi, A., Garza-Reyes, J.A., Belhadi, A., Kamble, S.S., Elbaz, J., 2021. A readiness self-assessment model for implementing green lean initiatives. J. Clean. Prod. 309, 127401. 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.

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

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. Bus. Strateg. Environ. 30 (7), 3255–3272. https://doi.org/10.1002/bse.2801.

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

De Oliveira, C.T., Dantas, T.E.T., Soares, S.R., 2021. Nano and micro level circular economy indicators: assisting decision-makers in circularity assessments. Sustain. Prod. Consum. 26, 455–468.

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 Techn. Environ. Policy 24 (5), 1535–1552.

De Paula e Silva, M.H., Barretti, J.W., Mergulhão, R.C., Silva, D.A.L., 2022a. 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.

De Paula e Silva, M.H., Costa, L.B.M., Paredes, F.J.G., Barretti, J.W., Silva, D.A.L., 2022b. The effect of demand forecasting choices on the circularity of production systems: A framework and case study. Resources, Conservation, and Recycling Advances 15, 200088. https://doi.org/10.1016/j.rcradv.2022.200088.

de Souza, C., 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.

Dieste, M., Panizzolo, R., Garza-Reyes, J.A., Anosike, A., 2019. The relationship between lean and environmental performance: Practices and measures. J. Clean. Prod. 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. J. Clean. Prod. 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. J. Clean. Prod. 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.

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

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. *Guia de Sustentabilidade para as Empresas*. 2007 www.ibgc.org.br.

Inman, R.A., Green, K.W., 2018. Lean and green combine to impact environmental and operational performance. Int. J. Prod. Res. 56 (14), 4802–4818. https://doi.org/10.1080/00207543.2018.1447705.

Jørgensen, F., Matthiesen, R., Nielsen, J., Johansen, J., 2007. Lean Maturity, Lean Sustainability. In: Olhager, J., Persson, F. (Eds.), IFIP — the International Federation for Information ProcessingAdvances in Production Management Systems. Springer US, Boston, MA, pp. 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. J. Manuf. Technol. Manag. 33 (6), 1059–1079.

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. J. Bus. Res. 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. J. Clean. Prod. 278, 123223.

Leme Junior, R.D., Nunes, A.O., Costa, L.B.M., Silva, D.A.L., 2018. Creating value with less impact: Lean, green and eco-efficiency in a metalworking industry towards a cleaner production. J. Clean. Prod. 196 (20), 517–534. https://doi.org/10.1016/j.jclepro.2018.06.064.

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. 30, 130–144. https://doi.org/10.1016/j.spc.2021.12.001.

Maasouman, M.A., Demirli, K., 2016. Development of a lean maturity model for operational level planning. Int. J. Adv. Manuf. Technol. 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* 296, 118755. 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. J. Clean. Prod. 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. J. Oper. Res. Soc. 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. Comput. Electron. Agric. 150, 62–73. https://doi.org/10.1016/j.compag.2018.03.034.

M. Rother S. John *Learning to See: Value Stream Mapping to Add Value and Eliminate MUDA*. 2003.

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. Environ. Impact Assess. Rev. 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. J. Clean. Prod. 318, 128531. 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.

Shevchenko, T., Saidani, M., Ranjbari, M., Kronenberg, J., Danko, Y., Laitala, K., 2023. Consumer behavior in the circular economy: Developing a product-centric framework. J. Clean. Prod. 384, 135568. https://doi.org/10.1016/j.jclepro.2022.135568.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. Strateg. Manag. J. 18 (7), 509–533.

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.

Urbinati, A., Chiaroni, D., Toletti, G., 2019. Managing the introduction of circular products: Evidence from the beverage industry. Sustainability 11 (13), 3650.

Verrier, B., Rose, B., Caillaud, E., 2016. Lean and green strategy: The lean and green house and maturity deployment model. J. Clean. Prod. 116, 150–156. https://doi.org/10.1016/j.jclepro.2015.12.022.

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