A methodology to analyze production process based on the implementation of a Circular Value Stream Mapping

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Abstract

Value Stream Mapping (VSM) is a Lean tool that visualizes and analyzes the flow of materials, information, and value through a production process. It plays a crucial role in identifying areas of waste and lost value, enabling process redesign for more sustainable production. To align with the Circular Economy (CE) principles, a methodology called Circular Value Stream Mapping Methodology (C-VSMM) was developed, integrating VSM with CE concepts. The development of C-VSMM offers a valuable tool for organizations to improve production processes and progress towards sustainability. Additionally, a questionnaire was created through a semi-structured interview to help companies in identifying opportunities for improvement. This questionnaire enhances the methodology by providing a comprehensive understanding of processes and facilitating targeted improvements. The integration of Lean principles, particularly VSM, with the CE concept expands the application of VSM, enabling companies to pursue sustainability goals and improve production processes. Overall, the study presents the C-VSMM as a practical and theoretical contribution, empowering companies to adopt more sustainable practices and achieve production process improvements aligned with the CE.

Keywords
Circular Economy, Lean Management, Circular Value Stream Mapping, Methodology, Sustainability.

1. Introduction
In a world where resources are limited, it is essential to move away from the traditional linear economic model and embrace a more sustainable approach. Circular Economy (CE) aims to keep resources in use for as long as possible, reduce waste and pollution, and regenerate natural systems. Targets can aid in the shift towards a CE through various means, such as minimizing waste, creating closed-loop production processes, optimizing resource utilization, and maximizing the economic value retention of materials and products (Morseletto, 2020). To achieve this, companies need to analyze their production processes carefully to identify opportunities to reduce waste, increase efficiency, and create value from waste products.

In the context of the CE, where the goal is to minimize waste and maximize the value of resources, Value Stream Mapping (VSM) can play a crucial role in achieving these objectives. By mapping the flow of materials, information, and value in a product or service's lifecycle, VSM can help identify areas where waste is being generated or where value is being lost. This information can then be used to redesign processes and systems to eliminate waste and maximize value. While the VSM is a valuable tool for enhancing operational efficiency, the Green VSM (Muñoz-villamizar et al., 2018) was introduced to enhance environmental performance as well. However, its representation remains limited if CE improvements wants to be identified (Kalemkerian et al., 2022). In this regard, some studies propose an extended version of VSM to incorporate CE strategies (Nascimento et al., 2022; Mangers et al., 2021; Hernandez Marquina et al., 2021). However, these studies do not provide a guide to identify the opportunities for improvement aligned with CE strategies.

Therefore, the aim of this paper is to present a methodology to analyze production process based on a tool called Circular Value Stream Mapping (C-VSM). The C-VSM is a tool developed by the authors, which is focused on the management of the resources that intervene in the production process and how the wastes are managed. The methodology proposed describes the steps to implement the C-VSM and to identify opportunities for improvement.

The study presented in this research paper makes significant contributions both in theory and practice. The theoretical aspect focuses on integrating Lean principles, specifically VSM, the concepts and goals of the CE. By incorporating VSM into a circular approach, the methodology proposed, provides a framework for analyzing and enhancing production processes in line with CE principles. This integration extends the application of VSM beyond traditional Lean practices, enabling companies to pursue sustainability objectives. In practical terms, by adopting the C-VSMM companies can gain a comprehensive understanding of their production processes. This understanding enables them to identify areas where waste is generated and value is lost, leading to targeted improvements. Redesigning processes and systems based on this analysis helps eliminate waste and maximize value, contributing to more sustainable production practices.

1.1 Objectives

The first objective is to present a C-VSMM by integrating VSM with CE concepts. Furthermore, the second objective is to create a questionnaire based on semi-structured interviews to identify opportunities for improvement in production process as part of the C-VSMM.

2. Literature Review

There is a substantial body of literature that has presented circular strategies for the industry. In the manufacturing sector a strategy for increasing circularity potential and process efficiency consists of using fewer natural resources or energy, treating emissions and waste properly, recycling and reusing wastes and scrap on site, recovering energy and nutrients, and using environmentally friendly transportation and driving (Kravchenko et al., 2019). According to Nobre and Tavares (2021) the 9R-Framework, Waste-Hierarchy, Clean and Renewable Energies and Resource Efficiency constitutes basic concepts of the CE. Nonetheless, the R-strategies as a whole, establish a framework in which a variety of alternatives and objectives may be used to encourage CE adoption (Morseletto, 2020). The R-strategies in the 9R-Framework are refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover (Potting et al., 2017).

Prior to the implementation of a strategic initiative, the initial and indispensable step entails the identification of opportunities. Consequently, the development of methodologies to analyze process become key in guiding organizations to effectively discern these opportunities. Such methodologies offer companies a systematic approach to identify, assess, and evaluate potential avenues for improvement. Ultimately, the best methodology will depend on the specific needs and goals of the organization, as well as the nature of the production process being analyzed.

One method to analyze production process is Statistical Process Control, which involves analyzing data to identify patterns or trends in the production process. By analyzing this data, organizations can understand the stability and capability of their production processes and make informed decisions for process improvement. Six Sigma is another methodology that uses statistical analysis to identify and eliminate defects in the production process. It combines statistical analysis, problem-solving methodologies, and project management techniques to achieve process improvements. Furthermore, there are some studies that implemented Six Sigma with DMAIC (Hakimi et al., 2018). DMAIC is an acronym for Define, Measure, Analyze, Improve, and Control. It is a structured problem-solving approach. DMAIC provides a framework for organizations to identify process issues, measure key metrics, analyze root causes, implement improvements, and establish control mechanisms to sustain the improvements over time.

Another widely employed tool is process mapping (VSM), where the entire production process is visually mapped out to identify areas of inefficiency or waste. VSM is one of the most widely implemented lean tools used to analyze the production process in the manufacturing sector. It is a comprehensive visualization tool, which is frequently applied to show the primary processes and their activities or subprocesses (Romvall et al., 2011). It makes it possible to observe and understand the information and material flow as a product moves along the value stream. The main aim of VSM is to help users to identify waste and eliminate or reduce it to improve operational performance.

The integration of VSM and CE may act as a catalyst for transitioning from linear systems to circular production systems, as highlighted by studies conducted by Lim et al. (2022). While there have been numerous studies proposing VSM methodologies for analyzing production processes (Vinodh et al., 2016; Muñoz-villamizar et al., 2018) there is a lack of methodologies that specifically address the analysis of production processes and guide the identification of improvement opportunities aligned with CE principles. According to recent research (Nascimento et al., 2022), the primary challenge in achieving circularity through continuous and incremental improvement lies in the lack of studies that propose a methodology incorporating a Lean Manufacturing tool. Therefore, this paper presents a new, innovative methodology to analyze production process called C-VSMM, with the aim of demonstrating how combining the CE and Lean can improve both productivity and environmental performance of the production process. The need to develop a methodology to analyze the production process is crucial to identify opportunities for improvement aligned with the CE. By implementing CE principles, companies can not only reduce their environmental impact but also improve their bottom line by reducing costs, increasing revenues and enhancing their brand reputation.

3. Methods

Semi-structured interviews were chosen as a qualitative research method for this study to create a questionnaire to identify opportunities for improvement in the production process. Internal testing within the research team was carried out and an extra interview was conducted for this reason. After adjusting the questions, a final version of the interview guide was created.

Since the main aim of the interviews was to refine the questionnaire proposed, experts from the manufacturing sector were selected. Each expert was specialized in one of these areas: energy, water, materials, and waste management and by-products. Four interviews were held primarily through online meetings due to the availability and location of the respondents. The interview process began with an introduction of the scope of the study, and then an overview of the interview´s current and past areas of work and their years of dedication to sustainability/CE. Table 1 shows a full categorization of each respondent with their corresponding letter to be used for future referencing. The interviews continued following the guide although the exact wording was not used and the follow-up questions varied according to the interviewee. All sessions were voice and video recorded and further notes were also taken. The average time of the interview was 45 minutes and after each interview, the recordings and notes were completely transcribed for further analysis.

Table 1. Interviewees' information

Expert	Sector	Focus	Position
A	Manufacturing company - agri-food sector	Energy	Energy manager
B	Manufacturing company - chemistry sector	Materials	Manager material procurement
C	Recycling sector	Waste and by-products	General Management of the National Association of the Recycling Industry
D	Manufacturing company- paper sector	Water	Sustainability Manager

They initial version of the questionnaire was proposed by the research team and based on the studies of Garza-Reyes et al., (2019b); Cagno et al. (2022) and EMF (2021). The initial version is presented in the Annexes section (Table 4). The experts were asked que following questions during the interview:

1. *According to your experience, do you think this question its suitable for identifying opportunities for improvement?*
2. *Do you think more questions should be added?*

Considering the input provided by experts, certain questions were kept unchanged, some were modified, and new questions were incorporated.

4. Results and Discussion

The proposed methodology is based on the implementation of a tool called Circular Value Stream Mapping. Figure 1 shows the steps that should be followed to implement the methodology. These steps are based on the steps to implement the traditional VSM, which involves mapping out the current state of a process, identifying areas for improvement, and designing a future state map that eliminates waste (Hedlund, Stenmark, Noaksson, and Lilja, 2020).

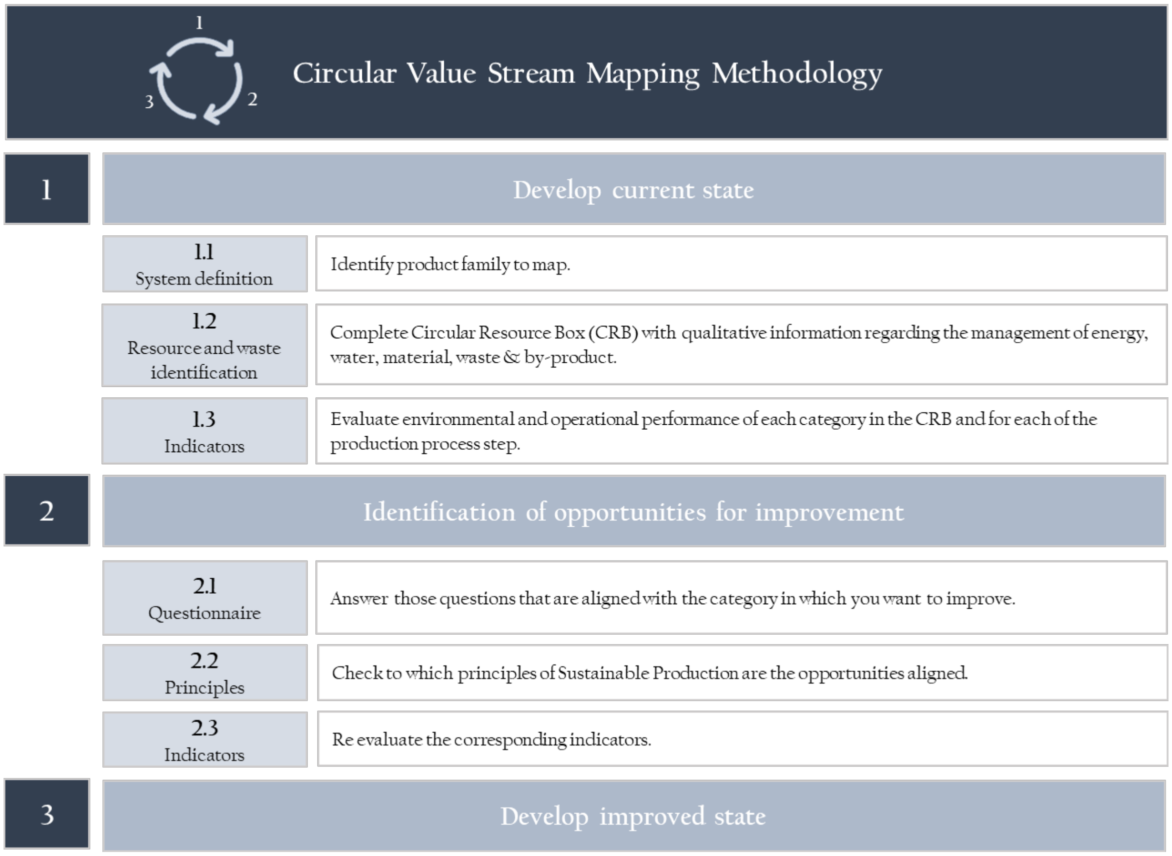

Figure 1. Circular Value Stream Mapping Methodology

1. <u>Develop current state</u>

The initial step involves creating a map of the present condition, which represents the existing or current state of the value stream or process being analyzed. It provides a visual representation of how resources, wastes, information, and activities flow within the system at a given point in time. This step is subdivided into three steps which guide in the developing of the current state.

1.1 System definition

The current state map, starts at the shop floor level. First, it is essential to determine the product family that will be mapped. Typically, companies label their systems according to their attributes, and each family has its own unique characteristics, which follow a distinct value stream and cross different organizational boundaries within the company. Therefore, it is crucial to clearly define the scope of the analysis. The boundaries may encompass, for example, from the acquisition of raw materials to the shipping.

1.2 Resource and waste identification and characterization

Once the specific product or product family has been identified, it is necessary to complete the Circular Resource Box (CRB). This box, depicted in Figure 2, should be filled with qualitative information about the resource management and waste generation at each step of the production process. Figure 2 illustrates four categories: material (including raw materials, parts, and components), energy, water, and waste and by-products. These categories visually represent the circular flow of resources. The CRB consists of two circles, an inner and an outer circle. The inner circle represents the outputs from the system, while the outer circle represents the inputs. These circles are included in the model to demonstrate the potential circular flows of resources both within and outside the organization. If there is any circular flow within the process, it should be incorporated as an indicator, displaying the percentage represented in colour (for example, the percentage of reused water entering the process).

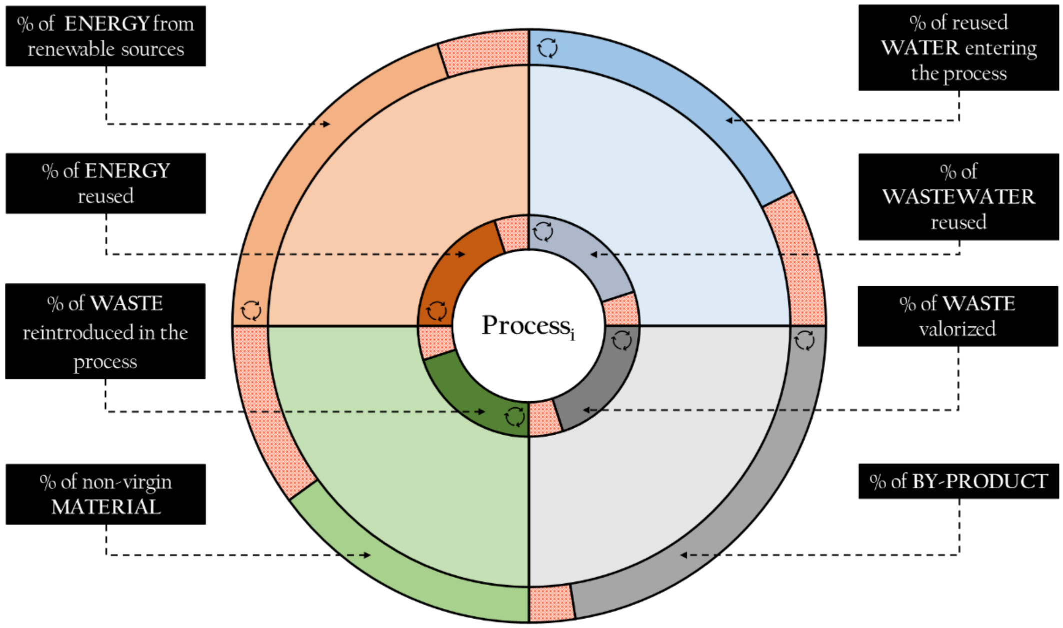

Figure 2. Circular Resource Box (authors´ creation)

The CRB should be completed for each production process step and integrated into the C-VSM, which provides valuable insights into how resources and wastes are currently being managed and what improvements could be made.

1.3 Indicators

In order to be able to identify opportunities for improvement, the qualitative information presented in each of the CRB, should be complemented with quantitative information about the operational and environmental performance of the process. The most appropriate metrics will vary depending on the company's circumstances, and different environmental metrics may be more relevant depending on the industry sector. In this regard, Brown et al. (2014) suggest that a smaller set of metrics, which are more widely applicable across different industries, can be more effective than having a full set of industry-specific metrics. In Table 2, we present a summary of the indicators that should be used in the C-VSM.

Table 2. Indicators to incorporate in the C-VSM

Domain	C-VSM	Indicators
Economic	Operational information	Cycle time
		Inventory
		Lead time
		OEE
Environmental	Inner circle	Amount of waste used/Total amount of waste generated
	Material	**Material consumption**
	Outer circle	Amount of non-virgin material /Total amount of material used
	Inner circle	Quantity of reused energy generated with process streams / Total energy consumption
	Energy	**Energy consumption**

Domain	C-VSM	Indicators
	Outer circle	Energy consumed from renewable sources / Total energy consumption
	Inner circle	Water reused entering the process / Total water consumption
	Water	**Water consumption**
		Waste water discharged
	Outer circle	Waste water reused entering the process / Total water consumption
	Inner circle	Waste reuse/Total waste generated
	Waste and by-product	**Amount of solid waste generation**
		Amount of by-products
	Outer circle	Total by-products generated/Total waste and by-products generated

2. **Identification of opportunities for improvement**

Once the current state is mapped, the next step involves identifying opportunities for improvement. To identify these opportunities, we propose a questionnaire that has a set of questions for each of the four categories of the CRB. To ensure that improvements are not made in isolation, we consider it relevant that these questions are aligned with sustainable production principles that provide a guide for the users, as well as a set of indicators that are aligned with these principles.

2.1 Questionnaire

As mentioned before, a questionnaire was designed to guide companies in the identification of opportunities for improvement. The final version of the questionnaire is presented in Table 3, which consists of 41 questions.

Table 3. Questionnaire to identify opportunities for improvement

Guiding questions to identify opportunities for improvement in the production process		
	Is the company analyzing ways to/has already implemented actions to / established plans to	
Energy	1	... reduce energy consumption (diesel, oil, natural gas)?
	2	... analyze whether any of the processes can generate energy to use inside the facilities?
	3	Does the geographic location allow for energy exchanges?
	4	... use energy generated by another company?
	5	…exchange the energy produced by the processes with another company?
	6	... substitute non-renewable energy sources with renewable ones?
	7	... invest in sustainable technologies to manage energy use?
	8	... register energy consumption (identify the different sources and types by stages of the production process)?
Water	9	... reduce the amount of water consumption?
	10	... change the sources of water?
	11	Is the company located in a water-stressed area?
	12	... reuse water internally?
	13	Does its geographic location allow for water exchange with other companies?
	14	... have the used and treated water be used by another company for subsequent use (external recirculation)?
	15	... use treated water from another company?
	16	Does the company ensure that all the water it uses is treated after being used?
	17	... include sustainability criteria for treating the water?
	18	... reduce the discharge of used water?
	19	... extract excess nutrients, metals, chemicals, heat, and similar valuable resources before discharging used water in its operations?
	20	... invest in sustainable technologies to manage water use?

Guiding questions to identify opportunities for improvement in the production process		
	21	... keep register of water consumption and discharge (identify the different sources and types by stages of the production process)?
Material	22	... reduce the amount of raw material introduced?
	23	... reduce or eliminate the amount of non-renewable raw material by substituting it with renewable raw materials?
	24	... include sustainability criteria when selecting the suppliers?
	25	Does your geographical location enable material/waste exchange with other companies?
	26	… analyze if other value chains that generate waste can use it as raw materials in your production process?
	27	... introduce reused or recycled raw materials?
	28	... substitute hazardous or toxic materials/substances?
	29	... change storage conditions (e.g., high energy consumption)?
	30	... find more applications with the same raw materials?
	31	... reduce/reuse/recycle the packaging of materials that arrive at the organization?
	32	... invest in sustainable technologies to manage raw materials use?
	33	... keep register of material consumption (e.g., discriminated by stage of the production process)?
Waste and By-products	34	... reduce or eliminate waste send to landfill?
	35	... separate waste?
	36	Does the flow in which it is producing allow it to do Industrial Symbiosis?
	37	... circulate waste (internally or externally), understanding waste as an input?
	38	… move to more favored actions for waste management according to the waste management hierarchy?
	39	... reduce or eliminate liquid or solid substances/materials that pose a threat to health and is listed as corrosive, harmful, irritant, reactive, or toxic?
	40	… invest in sustainable technologies to manage waste generation?
	41	…register of waste generation (i.e., differentiate by stage of the production process)?

2.2 Principles of Sustainable Production

Once an opportunity for improvement is identified, it is important to determine its alignment with the principles of sustainable production. The aim of the proposed methodology is that the improvements made by the company are oriented to improve the operational and environmental performance of production process, incorporating the principles of CE. For this reason, we consider pertinent to align the questions presented with some of the principles that characterize sustainable production. The principles developed by Viles et al. (2022) were considered relevant since they are focused on production process and are also aligned with the CE concept (see Figure 3).

Principles	
1	**Design for circularity**. Design processes, products, and packing to consume minimum natural resources and energy to sustain the ecosystem's regenerative capacities. Follow design for disassembly to allow - if possible - for recycling, repairing, reconditioning, refurbishing, or remanufacturing.
2	**Conserve resources and preserve their value.** Use the appropriate natural resources and energy for the desired sustainable goals. Preserve the value of resources for as long as possible within production facilities (internal recirculation) and consider the concept of industrial symbiosis to circulate resources (external recirculation).
3	**Manage waste sustainably.** Emphasize waste-prevention activities by reintroducing resources within the intended flow. For resources that reach the waste management stage, use the waste management hierarchy following these strategies: reduce waste, then reuse and recycle, minimizing all disposal routes, including landfilling and waste to energy.
4	**Pursue a risk-free environment.** Reduce or eliminate chemical substances, physical agents, and technologies that present a risk to the environment. Reduce GHGs emissions to reach net-zero emissions.
5	**Prioritize employees' well-being.** Embed employee safety and well-being in the day-to-day work. Choose practices and workplaces that preserve the physical, functional, and psychological comfort of employees.
6	**Enhance management commitment to sustainability.** Establish an organizational culture enabling high sustainability performance. Empower employees and develop their talents. Promote diversity, equity and inclusion in the workplace.
7	**Make a positive contribution to the community.** Contribute to better economic, environmental, social, cultural, and physical outcomes of the communities in which the company operates and in those where its decisions can have an impact.
8	**Promote value chain stakeholder collaboration.** Establish fluid communication and collaboration with all the stakeholders of your value chain to make processes and products more sustainable.
9	**Measure and optimize sustainable processes.** Define a set of "Key Performance Indicators" to optimize production processes. Monitor short- and long-term sustainability performance of the production system by encouraging digitalization.
10	Boost the use of sustainable technologies. Improve existing technologies with more sustainable alternatives, and provide information on both the potential benefits and risks to Sustainable Production. Consider Best Available Techniques; these techniques involve both the technology used and the design, construction, maintenance, and operation of the installation.

Figure 3. Principles of sustainable production extracted from Viles et al. (2022)

2.3 Indicators

When identifying an opportunity for improvement, it is important to measure its impact to determine whether it is a viable and beneficial solution. Therefore, once an opportunity for improvement is identified, it becomes crucial to engage in a process of re-evaluating the indicators proposed in the step 1.3. This step allows for a thorough assessment of the existing indicators' relevance and effectiveness in addressing the identified opportunity. By re-evaluating the indicators, the company can determine if they align with the specific goals and objectives of the improvement initiative. It also provides an opportunity to assess if the indicators adequately capture the desired outcomes and reflect the changes necessary for improvement.

3. Develop future state

Once an opportunity for improvement is identified, the next step is to map the future state, following step 1.

5. Conclusion

In conclusion, this research paper has introduced the Circular Value Stream Mapping methodology, which integrates the principles of Lean, specifically (VSM), with the goals and concepts of the Circular Economy (CE). The C-VSM provides a systematic approach for analyzing and improving production processes in alignment with CE principles, focusing on resource management and waste reduction. Different environmental metrics could be proposed according to the interests of decision makers. For example, if decision makers are primarily concerned with carbon emissions, then metrics related to carbon footprint could be developed and tested. By testing a range of environmental metrics, researchers can gain a better understanding of which metrics are most effective in different contexts, and how these metrics can be used to guide decision making. Additionally, the questionnaire presented, aims to guide companies in the identification of opportunities for improvement.

The study presented has both theoretical and practical contributions. Theoretical implications of this work lie in the integration of Lean principles, specifically the use of the VSM, with the concepts and goals of the CE. The CE emphasizes the efficient use of resources, reducing waste, and closing the loop in material cycles. By incorporating VSM into a circular approach, the methodology offers a guide for analyzing and improving production processes in alignment with the principles of the CE. This integration expands the applicability of VSM beyond traditional Lean practices and enables companies to pursue sustainability goals.

The practical implications of this study are significant. By applying the C-VSMM proposed in this study, companies can gain a comprehensive understanding of their production processes. This enables them to identify areas of waste generation and value loss, leading to targeted improvements. Redesigning processes and systems based on this analysis helps eliminate waste and maximize value, contributing to more sustainable production practices.
Future research should focus on implementing the C-VSMM real case studies.

References

Brown, A., Amundson, J., and Badurdeen, F. Sustainable value stream mapping (Sus-VSM) in different manufacturing system configurations: Application case studies. *Journal of Cleaner Production*, *85*, 164–179, 2014.

Neri, A., and Giambone, M. One Framework to Rule Them All : An Integrated , Multi-level and Scalable Performance Measurement Framework of Sustainability , Circular Economy and Industrial Symbiosis. *Sustainable Production and Consumption*, *35*, 55–71, 2022.

EMF. Indicadores, Circulytics, 1–43, 2020.

Garza-Reyes, J. A., Salomé Valls, A., Peter Nadeem, S., Anosike, A., and Kumar, V.A circularity measurement toolkit for manufacturing SMEs. *International Journal of Production Research*, *57*(23), 7319–7343, 2019

Gennitsaris, S., Oliveira, M. C., Vris, G., Bofilios, A., Ntinou, T., Frutuoso, A. R., … Dedoussis, V. Energy Efficiency Management in Small and Medium-Sized Enterprises: Current Situation, Case Studies and Best Practices. *Sustainability (Switzerland)*, *15*(4), 1–26, 2023.

Hakimi, S., Zahraee, S. M., and Mohd Rohani, J. Application of Six Sigma DMAIC methodology in plain yogurt production process. *International Journal of Lean Six Sigma*, *9*(4), 562–578, 2018.

Hedlund, C., Stenmark, P., Noaksson, E., and Lilja, J. More value from fewer resources: how to expand value stream mapping with ideas from circular economy. *International Journal of Quality and Service Sciences*, *12*(4), 447–459, 2020.

Kalemkerian, F., Santos, J., Tanco, M., Garza-reyes, J. A., and Viles, E. Analysing the alignment between the Green Lean and Circular strategies : towards a Circular Lean approach. *Journal of Manufacturing Technology Management*, *33*(6), 1059–1079, 2020.

Kravchenko, M., Pigosso, D. C., and McAloone, T. C. Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators. *Journal of Cleaner Production*, *241*, 118-318, 2019.

Lim, M. K., Lai, M., Wang, C., and Lee, S. Y. Circular economy to ensure production operational sustainability: A green-lean approach. *Sustainable Production and Consumption*, *30*, 130–144, 2022.

Mangers, J., Minoufekr, M., and Plapper, P. *Value Stream Mapping (VSM) to Evaluate and Visualize Interrelated Process-Chains Regarding Circular Economy*. *IFIP Advances in Information and Communication Technology* (Vol. 633 IFIP). Springer International Publishing, 2021.

Morseletto, P. Targets for a circular economy. *Resources, Conservation and Recycling*, *153*(October 2018), 104553, 2020.

Muñoz-villamizar, A., Santos, J., Garcia-sabater, J. J., Valencia, U. P. De, Grau, P., and Sebastian, S. *International Journal of Productivity and Performance Management*, 2018.

Nascimento, D. L. de M., Quelhas, O. L. G., Moyano-Fuentes, J., Tortorella, G. L., and Maqueira, J. M. Circular value stream mapping 4.0: Proposed general model and application to a digital 3D printing recycling factory. *Sustainable Production and Consumption*, *34*, 600–612, 2022.

Nobre, G. C., and Tavares, E. The quest for a circular economy final definition: A scientific perspective. *Journal of Cleaner Production*, *314*(December 2020), 127973, 2021.

Potting, J., Hekkert, M., Worrell, E., and Hanemaaijer, A. Circular Economy: Measuring innovation in the product chain - Policy report. *PBL Netherlands Environmental Assessment Agency*, (2544), 42, 2017.

Romvall, K., Kurdve, M., Bellgran, M., and Wictorsson, J. Green Performance Map – An Industrial Tool for Enhancing Environmental Improvements within a Production System. *Glocalized Solutions for Sustainability in Manufacturing*, (May), 2011.

Viles, E., Kalemkerian, F., Garza-reyes, J. A., Antony, J., and Santos, J. Theorizing the Principles of Sustainable Production in the context of Circular Economy and Industry 4.0. *Sustainable Production and Consumption*, *33*, 1043–1058, 2022.

Vinodh, S., Ben Ruben, R., and Asokan, P. Life cycle assessment integrated value stream mapping framework to ensure sustainable manufacturing: A case study. *Clean Technologies and Environmental Policy*, *18*(1), 279–295, 2016.

Biography

Florencia Kalemkerian
Florencia Kalemkerian holds a degree in Industrial Engineering from the University of Montevideo and has been involved in projects focused on implementing Lean Manufacturing tools in the industrial sector. Currently, she is pursuing a PhD at TECNUN-University of Navarra, where her research revolves around the integration of Lean Manufacturing principles with Circular Economy.

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Javier Santos is Professor at Engineering School (Tecnun – University of Navarra) in Spain. He has a PhD in Industrial Engineering and is a Lean Manufacturing expert, area in which he has been teaching for 25 years. As a researcher, he has supervised 9 PhD theses and is the author of 50 indexed scientific publications. He has also participated in 23 research projects, being the main researcher in 7 of them, highlighting the European project LIFE MCUBO (2016-2020). He is the main inventor of a patent. He has been Deputy Director of the Doctoral School of the University of Navarra (2012-2017). In 2006 he published the book "Improving Production with Lean Thinking" which has been translated into 4 languages.

Martín Tanco
Martin Tanco is the Dean of the Engineering School at the University of Montevideo. Previously, he was head of the Center of Innovation in Industrial Management (CINOI) at Universidad de Montevideo. He earned his Ph.D. in Industrial Engineering from the University of Navarra and holds an Industrial Engineering degree from Universidad de Montevideo. He has been actively conducting and publishing research in continuous improvement, design of experiments, and freight transportation. He is a researcher at Level II at ANII. Recently, he has led several public and privately funded projects, with the collaboration of several national and international institutions.

Patricia Rogetzer
Patricia Rogetzer finished her doctoral studies in Economics and Social Sciences at Vienna University of Economics and Business (WU) in September 2018, focusing on sustainable supply chains and the circular economy. In October 2018 she joined the chair of Logistics and Supply Chain Management at Technical University of Munich for two years as postdoctoral researcher. Since 1 October 2020, Patricia is Assistant Professor at the IEBIS department of the UT. Her research centers around sustainable supply chain management, dealing with trade-offs regarding economic, environmental and social issues as part of everyday decisions. She studies possibilities to make sustainability an integral part of business models and supports companies towards more sustainable decision-making.

Annexes

Table 4 presents the initial proposal of the questionnaire. In this context, qX refers to the questions presented in the initial version, while QX corresponds to the questions included in the final version of the questionnaire, with X denoting the question number.

Table 4. Initial version of the questionnaire

Categories	*Is the company analyzing ways to/already implemented actions to / established plans to*		Adjustments
Energy	1	…reduce the energy consumption (natural gas, diesel, petrol)?	Q1 in the final version.
	2	…substitute non-renewable energy sources with renewable ones?	Q6 in the final version.
	3	…reuse energy (external)?	Q5 in the final version, with minor changes.
	4	…utilize energy generated by another company?	Q4 in the final version, with minor changes.
	5	…analyze if any of your processes can produce energy?	Q2 in the final version. Referring to the possibility of using for its own production process.
	6	… invest in sustainable technologies to monitor and manage the energy?	Q7 in the final version. Removing “monitor”.

Categories	*Is the company analyzing ways to/already implemented actions to / established plans to*		Adjustments
	7	… better register and monitor your energy consumption (identify different sources and types per production process steps)?	Q8 in the final version. Removing "monitor".
	One more question was added (Q3)		
Water	8	…reduce the fresh water consumption?	Q9 in the final version with minor changes.
	9	…sharing used water with another company for further utilization (external recirculation)?	Q14 in the final version with minor changes.
	10	…reuse water (internal)?	Q12 in the final version.
	11	…utilizing water generated by another company?	Q15 in the final version.
	12	Is the temperature of your process a critical parameter that impedes you to reuse the water?	Removed.
	13	… incorporate sustainable criteria to pre-treat the water?	Q17 in the final version and replaces "pre-treat" by "treatment".
	14	… invest in sustainable technologies to monitor and manage the water?	Q20 in the final version. Removing "monitor".
	15	…register and monitor the water consumption and the water discharged (identify different sources and types per production process steps)?	Q21 in the final version. Removing "monitor".
	Four new questions were added (Q10, Q11, Q13, Q16). Two questions were added from waste category (Q18, Q19)		
Material	16	… include sustainability criteria in the selection of the suppliers?	Q24 in the final version with minor changes.
	17	…to reduce the amount of new material introduced?	Q22 in the final version.
	18	…reduce or eliminate the amount of non-renewable materials by substituting them with renewable materials?	Q23 in the final version.
	19	… introduce recycled or reused raw materials?	Q27 in the final version.
	20	… substitute hazardous or toxic materials/substances?	Q28 in the final version.
	21	… change the storage conditions (i.e., high energy consumption)?	Q29 in the final version.
	22	… deeper analyze how the shelf life of materials impacts on the production process?	Removed.
	23	… use the same materials for other products?	Q30 in the final version. Major changes.
	24	… reuse the packaging from the material that comes into the facility?	Q31 in the final version. Reduce and recycled were also added.
	25	… invest in sustainable technologies to monitor and manage the raw material?	Q32 in the final version. Removing "monitor".
	26	… register and monitor the consumption of material (i.e., per process step)?	Q33 in the final version. Removing "monitor".
	Two more questions were added (Q25, Q26)		
Waste and By-products	27	…reduce or eliminate the waste send to landfill?	Q34 in the final version
	28	… reduce waste water?	Q18 in the final version with minor changes.
	30	... extract excess nutrients, metals, chemicals, heat, and similar valuable resources before discharging used water in its operations?	Q19 in the final version.
	31	… separate waste?	Q35 in the final version.
	32	… circulate waste (internally or externally), understanding waste as an input?	Q37 in the final version.
	33	Do the European Waste Code help you to characterize your waste?	Removed.
	34	Is the flow in which you are producing, preventing you to do Industrial Symbiosis?	Q36 in the final version, change "preventing" to "allow".
	35	… reduce or eliminate any substance/material liquid or solid, which may present a threat to safety and health and is listed as corrosive, harmful, irritant, reactive, or toxic?	Q39 in the final version.
	36	… invest in sustainable technologies to monitor and manage the waste generation?	Q40 in the final version. Removing "monitor".
	37	… keep register and monitor the waste generation (i.e., per process step)?	Q41 in the final version. Removing "monitor".

Categories	*Is the company analyzing ways to/already implemented actions to / established plans to*	Adjustments
	One more question was also added (Q38)	

Energy
Regarding the energy category, it is crucial to differentiate between energy management, monitoring, and registration. Energy management involves tracking and systematically optimizing energy consumption within the company's facilities (Gennitsaris et al., 2023). "Monitor" was removed from q6 since according to the definition presented before, it is part of energy management. Since energy monitoring, involves analyzing energy consumption patterns to identify areas for improvement, "monitoring" was also removed from q7. In this regard, q7, refers to energy registration, which involves recording and tracking energy usage data over time.
The experts suggested to add one more question (Q3) in the energy category. Interviewee A make emphasis on the location of the company as an important aspect to consider when studying possible energy exchanges, all the interviews agreed to add this question. In this regard, interviewee B and D say that, analyzing the surrounding and how the company can take advantage of the other industries that are close and how they can make the energy exchange is key. The interviewee's company is located in an industrial hub and they make these exchanges because they analyze the geographic location. Therefore, Q3, "*Does its geographic location allow for energy exchanges?*" was added as a new question in the final version of the questionnaire.
Moreover, interviewee A proposed the inclusion of a question: "*What type of process is carried out? Is it stable or temporary?*" This question aimed to gather information about the nature of the company's production process. Interviewee A highlighted that the type of process directly influenced the potential for exchange that the company sought. As an illustration, interviewee A shared an example of their own company, which had excess energy in the form of heat and was located near another company that heavily relied on heat in their production process. However, due to the temporary nature of their own company's operations, with only two critical months, the other company expressed concerns about their ability to consistently meet the demand. Nonetheless, this specific scenario was not included in the final version of the questionnaire as it was considered unique to the case company.
Water
As in the energy category, some questions in the questionnaire were modified or added based on feedback from the interviewees. First, q12 was removed because cooling towers can address temperature concerns unless the temperature difference is very high. "If you have water available, the temperature can be addressed, and it should not be an impediment to reuse the water", according to interviewee A, and D.
Moreover, there were modifications made to q14 and q15 in the water category, removing the term "monitor". Additionally, interviewee B shared an interesting insight about a technology developed in Chile that enabled the utilization of saltwater in a desert golf course. This example highlighted the introduction of new technologies to change the water source, such as replacing fresh water consumption with saltwater, which is considered an "infinite" resource in that context. To address this aspect, a new question, Q10, was added to inquire whether the company is exploring ways to change its sources of water (*Is the company analyzing ways to change its sources of water?)*. This addition aimed to capture the environmental impact associated with different water sources, such as taking water from a river versus a waste treatment plant.
Additionally, three more questions were added (Q11, Q13, Q16). Regarding Q11 (*Is the company located in a water-stressed area?*), interviewee B mentioned that there are water stress zones, in which can have an impact on water management. Then, interviewee D commented on the importance of the location of the company to enable exchanges, Q13 was added (*Does its geographic location allow for water exchange with other companies?*). Furthermore, interviewee C emphasized the importance of water quality in these exchanges. In this regard, a question (Q16) was added regarding the treatment of the water after its use (*Does the company ensure that all the water it uses is treated after being used?*). To enable understanding, interviewer D also suggested to add all the information regarding water and wastewater in the same category. This is why there are two questions from the waste category that were moved to the water category (Q18, Q19).
Material
For the material category, only questions 23, 24, 25 and 26 changed. To enable better understanding, q23 was modified to suggest finding more applications with the same raw materials as a way to reduce the quantity of raw materials used. For q24, interviewee D suggested considering all three R's: Reuse, Recycle, and Reduce. Interviewee B mentioned some examples regarding the packaging that comes with the raw material, for example, the company could switch to using bulk packaging materials such as large bags or containers to reduce the amount of packaging waste generated. Considering reusing, they can use plastic bags or containers for multiple shipments or use cardboard boxes

multiple times by ensuring they are in good condition. Finally, if packaging waste is unavoidable, the company can ensure that the materials used are recyclable.

Additionally, similar to the modifications made in the energy and water categories, the term “monitor” was eliminated from q25 and q26. It is worth noting that technology can encompass various aspects, such as new materials or software that assist companies in managing their production processes and techniques. Consequently, q22, which was specific to the food sector based on feedback from the interviewees, was removed from the questionnaire.

Furthermore, interviewee B has drawn attention to specific questions that merit special consideration. In q16, the interviewee emphasized the growing importance of incorporating sustainability-related regulations, including for small and medium-sized businesses. Question 22 revolves around the reduction of raw material usage, which can be complex for final products but relatively simpler for packaging. The interviewee suggests reconsidering approaches to minimize the consumption of raw materials. As for Q29, the interviewee highlights the need to analyze the entire logistics chain rather than solely focusing on storage or transportation. However, considering the scope of the tool, the question remains unchanged in the final version of the questionnaire.

Finally, two more questions were added (Q25 and Q26) in this category as suggested by the interviewee B. Regarding Q25, it aims at identifying opportunities for collaboration with other industries in the surroundings of the company to exchange materials or waste (*Does your geographical location enable material/waste exchange with other companies?).* Q26 asks if it's possible for other value chains that generate waste to use it as raw materials in your production process. This question is aimed at identifying opportunities to turn waste generated by other industries or businesses into a valuable resource for the production process, *(Is the company analyzing if other value chains that generate waste can use it as raw materials in your production process?).*

Waste

In this case, most of the questions remained the same, q37 and q38, “monitor” was removed, following the same explanation as in the other categories. Then, two more questions were added as suggested by the experts. Interviewee C suggested to add Q38 (*...move to more favored actions for waste management according to the waste management hierarchy?*), which suggests transitioning from less preferred ways of waste management (such as disposal) to more preferred methods (such as prevention, minimization, reuse, and recycling) in order to prioritize environmental sustainability and resource conservation.

Regarding, q34, the European Waste Code (EWC) is a classification system used in Europe to identify and manage waste. However, due to its specificity and applicability only within the European region, it has been decided to remove it from the questionnaire. As the questionnaire aims to be applicable to every production process, it is necessary to use a more general waste classification system that can be used universally. However, it is important to note that while q34 was removed from the questionnaire, it does not restrict users from including it if they deem it necessary for their specific evaluation purposes.