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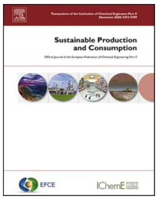

Value stream mapping for sustainability: A management tool proposal for more sustainable companies

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ABSTRACT

Few manufacturing companies consider sustainability aspects in their strategic planning. An alternative to overcoming this operational barrier is to integrate sustainability aspects into widely used management tools, with Value Stream Mapping (VSM) playing a prominent role. While the scientific literature offers attempts to incorporate sustainability aspects into VSM, most fail to comprehensively consider economic, social, and environmental capitals in an integrated manner. Furthermore, they often lack an epistemologically grounded conceptual model of sustainability. This study aims to propose the Value Stream Mapping for Sustainability (VSM4S), a model that combines the advantages of traditional VSM with the inclusion of sustainability aspects rooted in the concepts of the Five Sectors Sustainability Model (5SEnSU) and its related indicator named the Sustainability Synthetic Indicator of System (SSIS). As a result, all procedures for applying the VSM4S are presented in detail, making them replicable in any company. The VSM4S provides the SSIS for the company's planned future scenario under different strategic goals, as well as the cost-benefit ratio (B/C) and full-time equivalent (FTE) indicators. These three indicators are graphically represented in a cube-figure to facilitate the overall interpretation of different scenarios and to support more effective decision-making regarding which scenario should be implemented. While the operational applicability of VSM4S merits further attention, it effectively integrates sustainability aspects into a company's strategic planning, thereby promoting greater sustainability within and beyond the company's boundaries.

1. Introduction

Anthropogenic processes have led to a rapid pace of new product and process development, simultaneously increasing the pressure on the environment due to energy and material demands, as well as the ecosystem service of diluting concentrated by-products. In addition to other initiatives that aimed at understanding the human-nature relationship, such as Rockström et al.'s (2009, 2023) study on the planet's biophysical boundaries, the United Nations' Sustainable Development Goals (UN, 2023) recognize this issue. They propose a classification of objectives to be achieved with quantifiable targets, involving different scales and stakeholders in both public and private sectors. While advances towards sustainability can be found in government development plans (e.g., Teniwut et al., 2022; Yoshida, 2023; Muoneke et al., 2023) and in publicly traded companies' sustainability reports (e.g., Natura & Co. Group, Nestlé S.A., Siemens AG, Nike Inc.), the application of sustainability concepts in manufacturing companies is rarely found, regardless of their scale and product type. This is attributed to a variety of cultural barriers and factors such as time constraints, financial limitations, and the availability of skilled labor, as highlighted in the discussions by Mahmood et al. (2019), Ali et al. (2020), and Gohoungodji et al. (2020). For example, out of the total of 67 Brazilian companies included in the 2023 portfolio of the Corporate Sustainability Index (ISE) of the 'B3' stock exchange (ISE, 2023), despite representing 41 % (0.34 trillion USD) of the market value of all traded stocks, they exhibit an imbalance regarding the implementation of the UN SDGs in their businesses, ranging from 6 % for the "Life Below Water" SDG to 78 % for combatting climate change. In this sense, defining and understanding

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sustainability in its epistemology is important; otherwise, superficial and generic knowledge leads to disbelief in its implementation. Indeed, easily understandable concepts and models are needed to guide concrete and quantifiable actions in pursuit of sustainability (Gaikwad et al., 2020; Antomarioni et al., 2020).

Scientific literature indicates that methods used in diagnostics applied by manufacturing companies that supports their strategic planning are almost exclusively based on economic aspects, while environmental and social aspects are usually ignored. Consequently, companies are not fully effective in addressing potential causes that reduce their sustainability (Chiarini, 2014; Garza-Reyes et al., 2018; Mishra et al., 2019). On the other hand, due to the increasing need for the implementation of environmental and social management in the private sector to enhance competitiveness, sustainability must be included in their strategic planning. This new scenario results from increased societal pressure for more sustainable products, combined with stricter government regulations.

Various technical and managerial approaches aimed at improving quality and productivity have traditionally been considered within manufacturing companies to support decision-making, including kanban, 5S, Six Sigma, Poka-Yoke, 3Ms, SWOT analysis, 5W1H, and the 5 Whys. In this context, the Value Stream Mapping (VSM; Rother and Shook, 1999), based on the Toyota Production System, stands out as an important globally recognized management tool due to its objectivity and graphical representation of production flows, allowing for the identification of all kinds of production wastage on the factory floor. Although VSM is recognized as an important tool for increasing efficiency in the production system, its focus is mainly economic. On the other hand, current and fundamental production concepts such as cleaner production, circular economy, carbon markets, and improved labor relations need to be incorporated into the management of manufacturing companies aiming to expand their consumer market. One of the first attempts to incorporate environmental aspects into VSM was the so-called Sustainable Value Stream Mapping (SVSM) proposed by Simons and Mason (2002, cited in Faulkner and Badurdeen, 2014), which aimed to reduce greenhouse gas emissions in a supply chain. Although SVSM was recognized as important, it partially covered the environmental variable because it did not include other important indicators such as electricity consumption, water usage, and other materials used in processes, in addition to ignoring social aspects.

Recognizing the importance of having a VSM focused on sustainability, various alternatives have been proposed during last decade. Mohamad et al. (2019) used a standard SVSM toolkit provided by the United States Environmental Protection Agency (USEPA) in 2007 to integrate lean manufacturing and environmental practices, including material and water consumption in industrial processes. Norton and Fearne (2009) also included these similar indicators in SVSM to assess wastages in the UK food industry. With the aim of improving economic performance from the perspective of eco-efficiency as defined by the World Business Council for Sustainable Development, Vinodh et al. (2016) and Salvador et al. (2021) proposed the inclusion of Life Cycle Assessment (LCA) in VSM, resulting in the LCA-VSM model. Similar to USEPA studies, Litos et al. (2017) also proposed an integrated toolkit but focused on eco-efficiency. Based on the 'plan-do-check-act' (PDCA) continuous improvement cycle, Garza-Reyes et al. (2018) proposed an approach for systematically implementing environmental aspects in VSM, called 'Environmental-VSM' (E-VSM). Venugopal and Saleeshya (2023) proposed a sustainable VSM named as 'Sus-VSM' by including LCA indicators into the traditional VSM; authors applied the proposed method into wire manufacturing industry. Several other studies (Searcy and Elkhawas, 2012; Lasa et al., 2009; Helleno et al., 2017; among others) have discussed initiatives to alter VSM for reducing the environmental impacts of manufacturing companies, suggesting the inclusion of procedures and indicators for better environmental performance. In contrast to all these proposals that focus on the environmental issues, Gholami et al.'s (2019) study presented the VSM-Social, which allows for the visualization and evaluation of manufacturing performance using social indicators, including ergonomics and risks that may negatively affect employees. Advances in this approach may be achieved by incorporating social life cycle assessment (social-LCA), which addresses matters such as human rights, labor conditions, and cultural heritage considering different stakeholders, including the local community, society and consumers in general.

Despite advancements in making VSM more focused on sustainability, Faulkner and Badurdeen (2014) argue that there is a lack of clarity on how to incorporate environmental and social concepts practically and quantitatively in an integrated manner into the VSM. Based on a review of the literature on the subject, it was identified a lack of scientifically robust methods that allow for the inclusion of different stakeholders (suppliers, companies, customers, society) in VSM, while considering a multi-criteria approach and simultaneously assessing economic, social, and environmental indicators, rather than disaggregating them as suggested by other studies. Among other alternatives, the Five Sector Sustainability Model (5SEnSU; Giannetti et al., 2019) emerges as an alternative for multi-criteria sustainability conceptual model to be incorporated into VSM, aiming to provide mapping and planning in manufacturing companies with a focus on sustainability. The 5SEnSU allows for a holistic understanding of the relationships between the environment, the economic sector, and society as an open system, with the exchange of material, energy, and information. Donor and receiver functions are recognized for environmental and social sectors, which provide material resources, energy, and labor to the production system, receiving benefits such as quality of life and wages, or disadvantages such as waste, pollution, and poor working conditions. All these relationships are integrated into the 5SEnSU model, represented by different indicators, each with its respective concepts, methods, and units, resulting in a multi-criteria approach based on goal programming to calculate the Sustainability Synthetic Indicator of System (SSIS).

This study aims to propose the Value Stream Mapping for Sustainability (VSM4S), an approach resulting from the integration of the 5SEnSU model into VSM. The importance of VSM4S is justified by the deficiencies found in existing VSM proposals for sustainability, as found in the scientific literature. VSM4S requires the integration of various sectors within manufacturing companies, including sustainability teams, technical teams, and management teams, to assess holistic improvement opportunities in production processes, including economic, social, and environmental aspects. This study contributes to the proposal of a new tool for mapping wastages in manufacturing companies, but now with a focus on sustainability. It is expected that VSM4S can replace the traditional VSM as commonly considered in the decision-making process of manufacturing companies, resulting in diagnostics that enable the implementation of sustainability-seeking strategies.

2. Literature review

Before presenting the proposal for Value Stream Mapping for Sustainability (VSM4S), which is the objective of this study, it is important to introduce the key characteristics of traditional Value Stream Mapping (VSM) and present the Five Sector Sustainability Model (5SEnSU), which will be integrated into the VSM4S. The next two sections provide definitions, concepts, and procedures considered in both tools.

2.1. *Traditional value stream mapping (VSM)*

Value Stream Mapping (VSM) in its traditional structure was proposed by Rother and Shook (1999) with the goal of "seeing" the production flow more clearly, including material flows, energy, people, information, and more, typically measured in efficiency indicators to identify and reduce losses. An important step in the application of VSM is its schematic representation as shown in Figs. 1 and 2, which represents a "map" of the production system that will be used to focus on

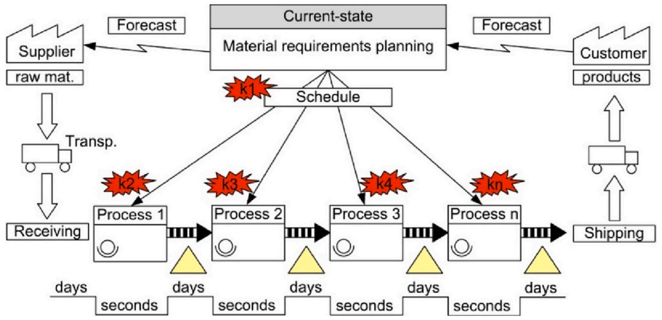


Fig. 1. Example of a value stream mapping (VSM) representing the current state of the manufacturing company. Symbols available in Appendix A.
Source: Rother and Shook, 1999.

management and production aspects that influence what will truly increase the value of the manufacturing company. While Fig. 1 represents the map of the current state of the company, Fig. 2 represents the map of the future state, serving as a guide to indicate what is intended to be achieved one year after implementing the strategic actions diagnosed in Fig. 1.

Both Figs. 1 and 2 have similarities in their interpretation, so they are described together here. The flow of information occurs from right to left, starting at the top of the maps with information flowing from the customer to the company's sales department and then to production planning and the raw material supplier. The material flow occurs from left to right, represented at the bottom of the map by industrial processes, where performance indicators (process time, waste rate, material consumption, etc.) are quantified for each process. The final step involves products being transported to customers. It's important to differentiate the map of the current state from that of the future state in terms of the production flow concept. The former typically operates on the so-called "push flow," while the latter operates on a "pull flow," which is a fundamental aspect of lean production to achieve higher eco-efficiency. Concepts like Industry 4.0, the Internet of Things, automation, big data, and others apply to lean production planning.

After obtaining the current state map (Fig. 1), the diagnostic stage begins with the distinction between activities that add value to the product (transformation activities) and activities that do not add value to the product. Activities that result in wastes, such as excessive time spent in production, time wasted on product quality recovery, ergonomic issues, and other factors that affect process efficiency and directly and negatively affect the company's economic indicators, do not add value to the product. It is essential to identify these activities using quantitative indicators that are compared to benchmarks or based on the expertise of the group of specialists responsible for the production processes; in Fig. 1, the indicator 'time' is used as example to represent the production process. Only after identifying the activities that do not add value to the manufacturing company, project proposals (referred to as 'kaizen') for improvements can be discussed for possible implementation.

The term "kaizen" is a combination of the Japanese words 'Kai,' which means change, and 'Zen,' which means better, an expression that has come to represent continuous improvement (Imai, 1986; Palmer, 2001; Malik and YeZhuang, 2006). The goal of kaizen is to eliminate wastages in production systems by adopting teamwork through motivation and creativity based on the concepts, methods, and tools of lean manufacturing. According to Womack and Jones (2003), kaizen considers lean manufacturing thinking as a systematic approach to wastage reduction, where wastage refers to activities that consume material and energy but do not add value to the manufacturing company. The application of kaizen can encompass numerous tools traditionally known in manufacturing systems, such as kanban, 5S, Six Sigma, Poka Yoke, and 3Ms, which, according to Suzaki (1987), they should all be based on the logical sequence of the PDCA continuous improvement cycle.

After defining the kaizen projects plan to achieve the goals established in the manufacturing company's strategic plan, the future state map is created (Fig. 2). The VSM of the future state graphically represents the expected scenario one year after implementing the kaizen improvement projects. Since the improvement process is continuous and cyclical, the future state VSM should be used as a reference as the kaizen projects are implemented because adjustments may occur during the planned improvement processes. Finally, in the review of the future state VSM after one year, it becomes the current state VSM, and a new future state VSM is developed based on the new goals set for the next year. This cycle repeats annually.

The intention here is not to exhaust the topic of VSM but to provide important elements for the reader to understand where the VSM4S proposed in this study fits. For more details on traditional VSM, it is recommended to refer to other studies, especially the seminal one published by Rother and Shook (1999), as well as others more recent, such as Dinesh et al. (2022) and Rathi et al. (2022).

2.2. *The five sectors sustainability model (5SEnSU)*

In order for anthropic systems to continue to produce and thrive, a systemic view is necessary to understand the relationships between humans and nature. According to Goodland and Daly (1996), nature acts

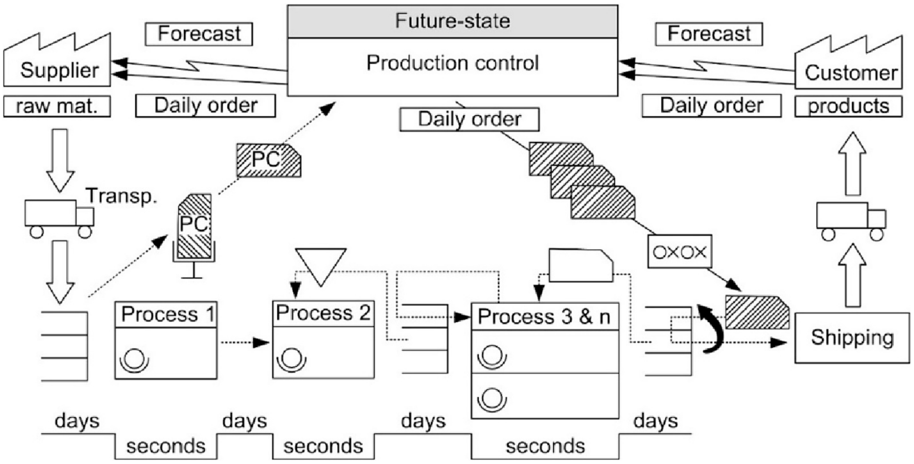


Fig. 2. Example of a value stream mapping (VSM) representing the future state of the manufacturing company. Symbols available in Appendix A.
Source: Rother and Shook, 1999.

in two ways to support human development: (i) as a supplier of resources (energy, fertile soil, water, minerals, wood, coal, oil, etc.), and (ii) as a sink for by-products with the function of reducing their concentration (known as natural purification). Under this biophysical view of the relationships between processes, the sustainability model is based on the understanding and respect for the Earth's biophysical limits to support growth, as advocated in Georgescu-Roegen's (1971) seminal study. The main idea is that social and economic development can only be achieved if natural capital is preserved, maintaining its biocapacity. Among other methods that consider this biophysical model for discussing sustainability are the Ecological Footprint (Wackernagel and Rees, 1996) and Emergy Accounting (Odum, 1996).

Other conceptual models of sustainability recognize that natural, social, and economic capitals are equally important, often complementary and/or partially interchangeable. With a focus on this perspective, one example is the Stockholm Resilience Centre (2023) used the UN SDGs as a wider and integrative proposal for a sustainability model considering all three capitals. Among other alternatives, the input-state-output model discussed in Pulselli et al. (2015) understands that all production systems on Earth are open systems with material, energy, and information flows between the environmental, social, and economic sectors. An advancement in this model is the Five Sector Sustainability Model (5SEnSU; Giannetti et al., 2019), which recognizes the donor and receiver functions of the environmental and social sectors. These and other features of the 5SEnSU model make it suitable for use in this present study, providing epistemological support for a conceptual sustainability model that makes the discussion more robust rather than relying on vague and unsupported concepts.

The 5SEnSU model, as represented in Fig. 3, consists of five sectors: the environment providing resources (S1), the environment receiving residues (S2), the production unit representing the economy (S3), the society providing resources (S4), and the society receiving residues (S5). Economic flows, represented by dashed lines, exist exclusively on the right side of the model, showing exchanges between the economic and society sectors. Giannetti et al. (2019) and Agostinho et al. (2019) present the procedures for applying 5SEnSU, which are summarized here. First, the system being studied is defined, which for the purposes of this study would be a manufacturing company. Next, the analyst must choose representative indicators for each of the five sectors of 5SEnSU. The minimum number of indicators is one, but there is no maximum number, and it is not necessary to use the same number of indicators for all sectors. The indicators are quantified using primary data obtained from the manufacturing company. Each indicator is calculated based on its own definitions, concepts, algebra, and units. Goals are established for each indicator, and weights of importance are assigned if necessary, as well as punishments for indicators that do not align with their maximization and/or minimization objectives; for this step, participatory meetings with different experts are recommended. Since the backbone of 5SEnSU is a multicriteria approach, the philosophy of goal programming is used to calculate the sustainability synthetic indicator of system (SSIS), which is the result of combining all the calculated indicators, including their weights and punishments. Agostinho et al. (2019) provide an Excel® spreadsheet with all these procedures automated (also available in the Supplementary Material A), which are explained in more detail in the following section proposing its application in the VSM4S.

According to Giannetti et al. (2019), the main advantages of the 5SEnSU model stem from its multi-characteristics: it has a multidimensional perspective as it includes economic, social, and environmental aspects; it adopts a multi-view approach by considering environmental, social, and economic perspectives; it is a multi-metric tool as it incorporates indicators with different units; it has a multicriteria approach by synergistically combining different indicators into a unique sustainability indicator. Despite being proposed in 2019, the 5SEnSU model has been used in various studies, including: Agostinho et al. (2019), who examined the sustainability of different modes of soybean transportation for export in Brazil; Moreno García et al. (2021), who assessed the sustainability of rice production in Brazil and Cuba; Terra dos Santos et al. (2022), who studied the relationship between sustainability and circularity of world trade blocs; Nascimento et al. (2022), who evaluated the economic-ecological performance of broiler chicken production; Giannetti et al. (2023), who discussed about the poverty traps in developing countries; Agostinho et al. (2023), who studied the influence of the expansion of the Brazilian agribusiness on the sustainability performance of the MATOPIBA region; and Pierucci et al. (2023), who applied the 5SEnSU model to discuss the sustainability of cities. As one can see, the usage of 5SEnSU model is increasing in different cases and becoming a scientific mature conceptual model of sustainability.

3. Methods

The proposed VSM4S in this study is based on the same calculation procedures as the traditional Value Stream Mapping (VSM) by Rother and Shook (1999), including aspects related to increasing profitability, operational efficiency, quality, and other economic interests of the manufacturing company. However, the traditional VSM still has gaps that can be overcome to achieve higher sustainability within the company, rather than solely focusing on economic aspects that may lead to a limited level of sustainability, as previously identified and discussed by Simons and Mason (2002, cited in Faulkner and Badurdeen, 2014), Vinodh et al. (2016), and Helleno et al. (2017). Compared to the

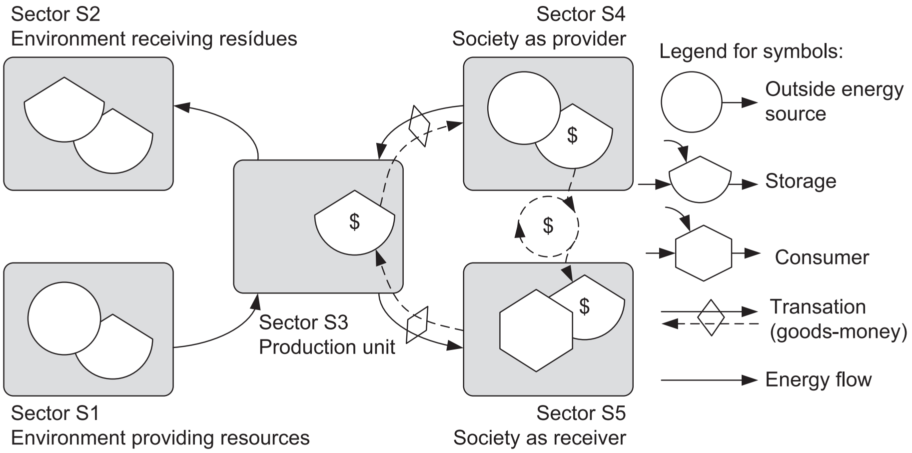


Fig. 3. The five sector sustainability model (5SEnSU).
Source: Adapted from Giannetti et al., 2019.

traditional VSM and other efforts to develop VSM with a sustainability focus (Norton and Fearne, 2009; Salvador et al., 2021; Cheung et al., 2017; among others), the VSM4S proposed in this study has a unique feature, which is the inclusion of multiple indicators covering both economic, social, and environmental aspects, grounded in the 5SEnSU model. Subsequently, a multi-criteria approach based on the philosophy of goal programming is used to calculate the Sustainability Synthetic Indicator of System (SSIS), representing the sustainability performance of the manufacturing company being assessed.

Before presenting the proposed model, it is important to emphasize that in manufacturing facilities with long and complex production lines, it often becomes unfeasible to apply mapping to all parts and production lines. When this occurs, the scope representing partially the entire manufacturing process needs to be defined and tackled. To do this, the team of specialists develops a “product-process” matrix considering the main product families that will be part of the mapped flow, including all processes considered in the production flow. According to Rasi et al. (2014), this matrix is defined based on the number of processes a particular product will undergo, meaning that the higher the number of processes for a specific product, the higher priority it receives for integration into the mapping. This criterion allows for more opportunities for improvements in manufacturing, with more significant gains throughout the considered flow for mapping, as this product can affect and/or include different processes in manufacturing. More details on this matter can be seen in Rother and Shook (1999), among others.

Fig. 4 presents the flowchart with the steps of the proposed VSM4S. Initially, the VSM4S is applied for the diagnosis of the current state, then environmental, social, and economic indicators of the evaluated production flow are chosen and calculated, using the 5SEnSU model as a reference, ultimately resulting in the SSIS for the current state. For the development of the VSM4S in the future state, the steps are similar to those in the current state VSM4S, but it includes the creation step of different Kaizen projects that should be completed based on the goals set in the company’s strategic planning for the next twelve months. Since various Kaizen projects can be developed, different results in environmental, social, and economic company’s performance will be achieved, resulting in different SSISs. Fig. 4 is used as a reference to explain the steps for applying the VSM4S in detail, as presented in the following sections.

3.1. VSM4S representing the current-state

3.1.1. Choosing environmental, social and economic indicators for the VSM4S

To calculate the SSIS for the current state (item (a) in Fig. 4), the 5SEnSU model needs to be supplied with economic, environmental, and social indicators. According to Giannetti et al. (2019), there is no maximum limit on the number of indicators, but a minimum of five indicators is required, with one indicator representing each of the five sectors in 5SEnSU. To select a set of sustainability-related indicators and define a way to integrate them into company strategies, Hristov and Chirico (2019) suggest two approaches. The first approach involves a systematic literature review to identify key performance indicators (KPIs) commonly used by managers in the development of sustainable performance strategies for manufacturing companies. The second approach is based on interviews (direct or indirect, such as surveys) with manufacturing company managers who typically have practical experience in using approaches like the balanced scorecard with various focuses beyond the economic aspect to assist in integrated company management. A third approach would involve collective participation in participatory meetings, including the team of company specialists responsible for implementing the VSM4S. An important role in choosing indicators is the representativeness of the indicator for the evaluated system and its relevance to the sustainability theme, which can vary among different types of manufacturing companies.

Traditionally, examples of indicators used in VSM with an economic focus include lead time, process cycle time, waiting time between process steps, defect rate in production, work-in-process inventory level, and resource utilization rate. However, it is important to note that the proposed VSM4S also requires indicators of environmental and social performance in addition to economic ones. While there is no standard for selecting indicators to feed into the 5SEnSU model, Table 1 provides suggestions based on a literature review on the subject. Indicators can be of the “higher is better” or “lower is better” type. In any case, it is crucial that the chosen indicators are grounded in and respect the five sectors of the 5SEnSU model, including their ‘donor’ and ‘receiver’ functions, following the rules presented by Giannetti et al. (2019). For example, an indicator related to the environmental sector S1 as a donor (e.g., water demand in m3/unit produced) should never be allocated to another

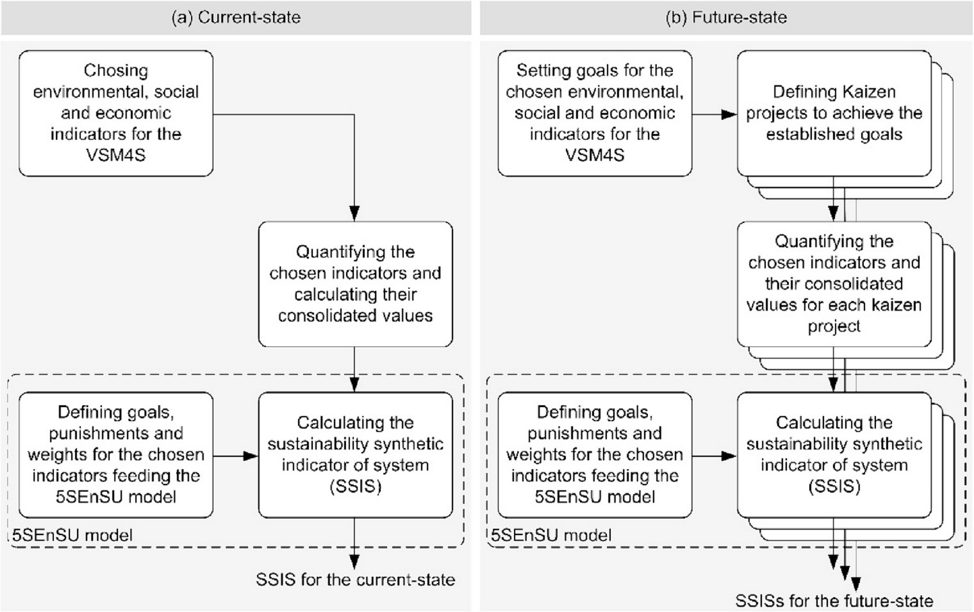


Fig. 4. Steps to apply the proposed value stream mapping for sustainability (VSM4S), including (a) current-state and (b) future-state calculation procedures. SSIS = sustainability synthetic indicator of system.

Table 1
Examples of indicators used in sustainability studies of manufacturing companies.

Economic indicators
Labor cost, energy use cost, consumables costs, maintenance costs, cost of byproduct treatment, indirect labor cost, (no)value-added time & cost, raw material consumption, total energy consumption, oil and coolant consumption, power consumption.

Environmental indicators
Greenhouse gas emissions from energy consumption, ratio of renewable energy used, total water consumption, mass of restricted disposals, noise level outside the factory, in-line energy consumption, energy consumption to maintain the facility environment, energy consumption for transportation into/out of the line, renewable energy ratio use, mass of disposed consumables, consumables reuse ratio, mass of mist generation, mass of disposed chips and scraps, ratio of recycled chips and scraps, carbon footprint, water eutrophication, air acidification.

Social indicators
Chemical contamination of working environment, mist/dust level, noise level inside factory, physical load index, health-related absenteeism rate, exposure to corrosive/toxic chemicals, exposure to high energy components, injury rate, physical load index, work environmental risks, labor demand, labor training.

sector other than S1, and so on. There is no maximum number of indicators to be used, but at least one indicator for each sector of the 5SEnSU model must be chosen; otherwise, the philosophy of goal programming cannot be applied. When there are doubts about whether an indicator is appropriate for a particular sector, it is recommended to discuss with other experts in participatory meetings. Data availability can be considered a limiting factor in the selection of indicators, which may lead to the use of one type of indicator over another, potentially judged as more representative of the studied system. In any case, the final report should clearly document the criteria adopted and choices made.

Based on Lu et al. (2011) and Vinodh et al. (2016).

3.1.2. Quantifying the chosen indicators and calculating their consolidated values

Once the indicators that will feed the 5SEnSU model have been chosen, they should be quantified using primary data obtained on-site (factory floor) for accuracy in the results. Secondary data should be avoided as much as possible but can be used when necessary. The calculation of each indicator should adhere to its own calculation rules, definitions, and procedures, as well as its original units. For example, while 'direct' indicators such as electricity (in kWh/unit) or water (in m^3/unit) consumption are quantified directly within the processes included within the spatial boundaries of the VSM, 'indirect' indicators such as those derived from life cycle assessment (e.g. global warming potential in $kgCO_{2\text{-eq.}}$/unit) must adhere to the definitions, rules, and algebra of LCA methods.

Similar to traditional VSM, the proposed VSM4S also aims to analyze the flow of materials, energy, and information that occurs in a production process, identifying wastages and proposing improvement opportunities. Therefore, just like traditional VSM, once the performance indicators to be represented in VSM4S are defined, and their values are obtained, their respective consolidated results are then calculated. Table 2 presents an example of a production flow with 'n' processes, showing different criteria for calculating the consolidated results of the indicators, which represents the overall performance of all production processes. The different criteria considered for calculating the consolidated results depend on the characteristics of each indicator, where two possibilities are possible:

(1) When there are indicators of processes that can be summed to represent the total system performance, the sum should be related to a functional unit, which is usually the quantity produced in units, mass, or volume of products. Table 2 shows greenhouse gas emissions as an example of this type of indicator. Other examples of indicators that follow this criterion are energy consumption, water consumption, as well as the consumption of other production inputs.

(2) When there are indicators that cannot be summed to represent the overall system performance, the consolidated result considers the process with the worst performance as the limiting factor among the others. Table 2 shows the operational efficiency and noise level as examples of this type of indicator, where for the former, the lowest value indicates worse performance (process P3 with 65 %), and for the latter, the highest value indicates worse performance (process P1 with 55 dB).

It is important to emphasize that the calculation of the consolidated results of the indicators is a necessary step to apply the VSM4S, as these values will feed the 5SEnSU model to calculate the sustainability indicator SSIS.

3.1.3. Defining goals, punishments and weights for the chosen indicators feeding the 5SEnSU model

This stage basically involves using the procedures of the 5SEnSU model as presented in Giannetti et al. (2019). Examples of the application of 5SEnSU can be found in Moreno García et al. (2021) in the sustainability assessment of rice production, Terra dos Santos et al. (2022, 2023) assessing the relationship between circular economy and sustainability, and Giannetti et al. (2022) evaluating water and wastewater treatment plants. Specifically, in this stage, goals, punishments, and weights for importance are defined for the consolidated results of each previously calculated indicator.

Since the philosophy of goal programming is considered a

Table 2
Hypothetical indicators value to exemplify the calculation of consolidated results in the traditional VSM and proposed VSM4S.

Indicators	Processes					Consolidated results	Criteria in obtaining the consolidated result
	P1	P2	P3	P4	Pn		
GHG emissions ($kgCO_2$/FU)	0.4	0.5	0.2	0.3	0.1	1.5	Total GHG emissions
Operational efficiency (%)	80	75	65	95	85	65	The lowest value for efficiency
Noise level (Db)	55	35	25	48	45	55	The highest noise level

FU means functional unit (e.g., amount of production in mass, units, volume, etc.).

multicriteria approach in modeling the 5SEnSU to quantify the sustainability synthetic indicator of system (SSIS), it is necessary to initially establish goals for the consolidated results of each indicator. The SSIS is quantified by considering the distance to the goal of each indicator (Fig. 5), and after the weighting process, these distances can be summed to represent the system's sustainability performance. Similar to the step of choosing indicators, Agostinho et al. (2019) emphasize that goal setting can be established through different approaches, including: the analyst's expertise according to the evaluated case study; participatory meetings where experts from different fields of knowledge can reach a common agreement; through government or corporate plans and reports that provide benchmarks. Objectively, benchmarks should have priority, but one can consider average values of the indicator in the sample (or another statistical variable) as considered by Terra dos Santos et al. (2022) as a goal. Another option is to adopt the best-performing indicator in the sample as the goal (Agostinho et al., 2019), when possible. Regardless of the criterion adopted by the analyst, the reasons for its use should be clearly presented.

Regarding punishments, since the philosophy of goal programming is based on the distance that the consolidated indicator result has from the established goal, the indicator is punished when it is below the goal and the objective is to maximize the indicator, or when the indicator is above the goal and the objective is to minimize it. Fig. 5 presents an example of punishment where the objective is to minimize the indicator. It can be observed that indicators of systems #2 and #4 are above the goal, so they should receive a higher punishment than the indicators of systems #1 and #3 that are below the established goal. When the objective is to maximize the indicator, the reverse logic is applied. Among the various ways to apply punishments, the use of the approach based on the Eco-indicator 99 (Goedkoop and Spriensma, 2001), which was further modified, used, and made available in Oliveira et al. (2016) and Agostinho et al. (2019), is suggested. In short, punishment values of 4.9, 2.3, and 1.8 for the social, environmental, and economic dimensions (based on an individualist analyst's cultural perspective) are suggested.

Regarding weights, the analyst can assign importance weights to each indicator and/or to each sector of the 5SEnSU model. The use and assignment of weight values depend on the analyst's experience and the study's objectives, but it is recommended to maintain a balance among the environmental, economic, and social sectors, where all indicators and sectors of the 5SEnSU are considered with equal weight of one. If assigning weights is considered important, it is suggested that the values to be assigned are obtained from participatory meetings with experts, or other scientific-based method. It is suggested to use a participatory method for selecting weights whenever possible. These methods are based on the exchange of knowledge, experiences, feelings, collaborative problem-solving, and collective knowledge construction processes facilitated among the individuals comprising a group. Among others, the Delphi method (Williamson, 2002) emerges as an alternative, involving a team of company experts. As auxiliary tools, for instance, the Analytic Hierarchy Process (AHP) can be also employed. Independently of the criteria considered in establishing weights, the choices should be clearly presented.

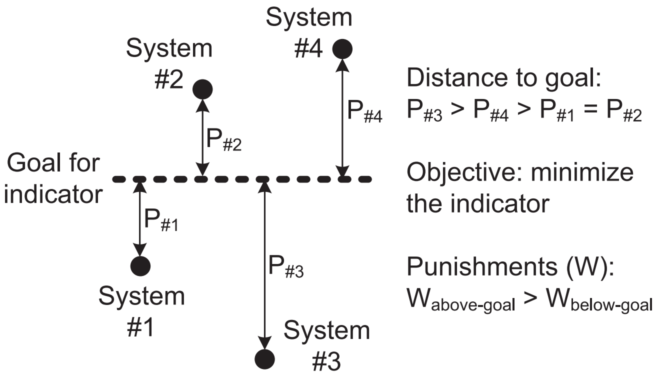


Fig. 5. Schematic example representing the goal programming philosophy considered in the 5SEnSU model.
Adapted from Giannetti et al. (2019).

3.1.4. Calculating the sustainability synthetic indicator of system (SSIS)

After selecting and quantifying the consolidated results for all environmental, social, and economic indicators, as well as defining their goals, punishments, and weights, the mathematical modeling that underlies the philosophy of goal programming can be applied. The calculation of SSIS is done following these steps: (i) After selecting the performance indicators for the environmental, economic, and social aspects of the company and distributing them among the 5 sectors of the 5SEnSU model, primary data is obtained through mapping the production flow (called as inventory step), indicators are calculated, and their respective consolidated results are obtained. (ii) The next step is the assignment of goals, punishments, and weights to different indicators based on their relative importance for overall sustainability. (iii) Finally, the SSIS is calculated using Eqs. (1)–(4), which in a simplified manner represent the mathematical modeling as originally presented by Giannetti et al. (2019) and later updated by Agostinho et al. (2019).

Eqs. (1) and (2) show the entire process of normalizing the consolidated results of the indicators, considering the distances to the goals (N and P) and the punishments (W) according to the objectives of maximizing or minimizing the indicator, resulting in the Index of Sustainability Goal of Indicator (ISG).

$$ISG^{+}_{ijk} = \sum_{ijk} \frac{N^{+}_{ijk}}{W^{+}_{jk}.G^{+}_{jk}} + \sum_{ijk} \frac{P^{+}_{ijk}}{W^{-}_{jk}.G^{+}_{jk}} \forall i \in \{1, 2, \ldots, NE\} \forall j \in \{1, 2, \ldots, NS\}, \forall k \in \{1, 2, \ldots, NI\} \tag{1}$$

$$ISG^{-}_{ijk} = \sum_{ijk} \frac{N^{-}_{ijk}}{W^{-}_{jk}.G^{-}_{jk}} + \sum_{ijk} \frac{P^{-}_{ijk}}{W^{+}_{jk}.G^{-}_{jk}} \forall i \in \{1, 2, \ldots, NE\} \forall j \in \{1, 2, \ldots, NS\}, \forall k \in \{1, 2, \ldots, NI\} \tag{2}$$

where: ISG = index of sustainability goal of indicator;

N^{+}_{ijk} and N^{-}_{ijk} = positive and negative indicators for the negative deviation variables, respectively;

P^{+}_{ijk} and P^{-}_{ijk} = positive and negative indicators for the positive deviation variables, respectively;

G^{+}_{jk} and G^{-}_{jk} = goals for the positive or negative indicators;

W^{+}_{jk} and W^{-}_{jk} = the punishment for each indicator;

NE, NS, and NI are the amount of evaluated systems, sectors, and indicators per sector, respectively;

i, *j*, and *k* represents the system being evaluated, the correspondent sector to the 5SEnSU model, and the indicator(s) for each sector, respectively.

The ISG is a measure of how far the indicator is from its goal, considering the chosen punishments. When adding all the ISGs of a sector and applying the weight of importance for sector (WS) if necessary, the sector sustainability indicator (SSI) is calculated by Eq. (3). Since the 5SEnSU model has five sectors, five SSIs are obtained.

$$SSI_{ij} = WS \sum_{ijk} \left(ISG^{+}_{ijk} - ISG^{-}_{ijk} \right) \forall i \in \{1, 2, \ldots, NE\}, \forall j \in \{1, 2, \ldots, NS\}, \forall k \in \{1, 2, \ldots, NI\} \tag{3}$$

where: WS = the weight of importance established for each sector.

Finally, the sustainability synthetic indicator of system (SSIS) can be obtained by adding the SSIs (Eq. (3)) of each sector as expressed by Eq. (4):

$$SSIS_i = \sum_{j}^{5} SSI_{ij} \forall i \in \{1, 2, \ldots, NE\}, \forall j \in \{1, 2, \ldots, NS\} \tag{4}$$

As a means to facilitate the calculation of SSIS, the Supplementary Material A provides an Excel® spreadsheet containing the goal programming philosophy as per Eqs. (1)–(4). The calculated SSIS represents the sustainability of the manufacturing company in its current state (Fig. 4a), as required in the first diagnosis step by VSM4S.

3.2. VSM4S representing the future-state

3.2.1. Setting goals for the chosen environmental, social and economic indicators for the VSM4S

The steps to carry out the VSM4S for the future state (item (b) in Fig. 4) are similar to the VSM4S for the current state, with the main differences lying in establishing strategic goals for the manufacturing company for a year (referred to as VSM4S goals) and proposing different Kaizen improvement projects to achieve these VSM4S goals. Defining VSM4S goals is crucial to enhance planning effectiveness, whether in a supply chain or production process (Rother and Shook, 1999). In this step, based on the results of the previous twelve months as represented by the VSM4S indicators in the current state, a team of multifunctional experts operating within the manufacturing system should discuss and propose goals for all indicators to be achieved in one-year period. The VSM4S goals must be aligned with the company's strategic objectives.

The way to discuss and establish goals for the traditional VSM is a well-known and practical procedure already used by manufacturing companies, and the same approach is considered in VSM4S. The established VSM4S goals and the planning on how to achieve them should be clear, measurable, and have established deadlines for the implementation of Kaizen projects. It is important to highlight that the goals should be validated by the company's decision-makers. Unlike the traditional VSM, setting VSM4S goals should not solely include economic indicators (e.g., increasing efficiency by 5 % or reducing losses in a particular operation by 10 %) but should also include goals for selected social and environmental indicators that feed the 5SEnSU model. For example, increasing the demand for skilled labor by 15 %, reducing noise by 4 %, reducing greenhouse gas emissions by 30 %, among others. Over time, as improvements are implemented and goals are monitored, new improvement opportunities may be identified within the concept of continuous improvement, claiming for adjustments to previously made decisions.

3.2.2. Defining Kaizen projects to achieve the established goals

After establishing the VSM4S goals for each economic, social, and environmental indicator that feeds the 5SEnSU model, the team of experts proposes practical planning options for improvement (Kaizen projects) with the aim of achieving the established goals within a one-year period. This is already a well-known and applied practice in manufacturing companies that utilize the traditional VSM. The quantity of Kaizen projects considered in the activity plan for the upcoming period, as well as the importance of the sized projects, will both be defined based on the established and previously validated VSM4S goals. The proposal for Kaizen projects can encompass management and technology/process aspects on how to operationalize the improvement suggestions.

It is important to emphasize that at this stage, several Kaizen projects may be proposed to achieve the VSM4S goals of the company's strategic plan, each project with a different primary objective and execution strategy. In VSM4S, there is unlikely to be just one single Kaizen project capable of achieving all the goals, instead there are various possibilities to reach the same objective. As a result, there are different scenarios (multiple boxes in the 2nd step of Fig. 4b) for strategic planning, where although the economic, social, and environmental indicators are the same in all scenarios, their quantitative final values may be slightly different, resulting in different SSISs, one for each scenario.

3.2.3. Quantifying the chosen indicators and their consolidated values for each Kaizen project

The procedure for calculating the VSM4S indicators for the future state and their respective consolidated results follows exactly the same process described for the VSM4S of the current state (2nd step of Fig. 4a). The difference lies in the quantity of values representing the consolidated results of the indicators, as there is a different scenario for each Kaizen project. Each scenario has different values for the economic, social, and environmental indicators, resulting in different consolidated results for the indicators.

3.2.4. Applying the 5SEnSU model to calculate the sustainability synthetic indicator of system (SSIS)

As shown in Fig. 4b, the other steps for calculating the SSIS of the VSM4S for the future state are similar to calculating the SSIS of the VSM4S for the current state. To ensure consistency in the results, the goals of the 5SEnSU model for the VSM4S of the future state are exactly the same as the goals established previously for the VSM4S of the current state. The application of the 5SEnSU model to the VSM4S of the future state also follows the same procedure, including the mathematical modeling that supports the goal programming philosophy (Eqs. (1)–(4)) automated in an Excel® spreadsheet. As a result, there are different SSISs, one for each scenario established according to each Kaizen project. The calculated SSISs can be ranked to identify the Kaizen projects that would result in higher or lower sustainability for the manufacturing company. It's important to remember that a lower SSIS value indicates higher sustainability since the system is closer to the established goals for the economic, social, and environmental indicators.

3.2.5. Choosing the best scenario for implementation: the cube-based decision

Since different Kaizen projects will result in different SSISs, a decision must be made on which project to implement. As usual in manufacturing companies, the decision on which project to implement also takes into account monetary and effectiveness aspects, which are generally represented by the benefit-cost ratio (B/C) and full-time equivalent (FTE) indicators. While the former focuses on the monetary aspect, the latter focuses on the availability of qualified labor within the company that can be allocated to implement the project. As a result, various scenarios can be provided to the decision-maker, each with its respective performance indicators for SSIS, B/C, and FTE.

As there are three indicators that would support a decision, it is suggested to represent them graphically using the assistance of a Cube figure, which would initially convey the information effectively. The cube has already been used to graphically represent the performance of different systems, as seen in the study of Coscieme et al. (2013), which considered indicators such as eco-exergy, environmental services, and emergy to assess ecosystems from a thermodynamic approach. Other examples Pulselli et al. (2015) that classified world economies according to their level of sustainability in a cube, expressing the performance of economies through indicators such as GDP, GINI index, and eMergy, the study by Sporchia et al. (2021) on the sustainability of European countries in a historical series measured by indicators such as GDP, CO2 emissions, and employment rate, and the study by Clasen et al. (2022), which proposed the use of the cube as an approach to study the nexus between food, energy, and water (FEW nexus) for municipalities.

For each Kaizen project that resulted in a possible implementable scenario, there is a value for SSIS, a value for B/C, and a value for FTE. To place these values in the cube, the first step is to adjust the interpretation of the indicators. For SSIS and FTE indicators, which are interpreted as 'the higher the value, the worse the performance,' both must be inverted (1/SSIS and 1/FTE) before representing them in the cube. For the B/C indicator, which is interpreted as 'the higher the value, the better the performance,' it can be used directly in the cube. The second step involves normalizing the indicators between 0 and 1. There are different normalization techniques available, but it is suggested to use the maximum-minimum normalization: Index ‘n’ normalized = (index ‘n’ - lower value for ‘n’ in the sample) / (higher value for ‘n’ in the sample - lower value for ‘n’ in the sample). The sample considered in the normalization process includes the different scenarios obtained through VSM4S, representing comparative performance. This normalization is simple to perform, quick to apply, and achieves the goal of placing the data in the cube. After normalizing the values, they can finally be placed in the cube, respecting the corresponding axes as shown in Fig. 6. There are 8 subcubes within the larger cube, where each subcube represents a different overall performance based on the combination of SSIS, B/C, and FTE indicators. Precisely, the following classifications are found: (i) totally unviable, (ii) executable only, (iii) economically viable, (iv) sustainable only, (v) economically viable and executable, (vi) sustainable and executable, (vii) sustainable and economically viable, (viii) fully viable. The first classification represents the worst scenario among all, followed by scenarios ii to iv, which show good performance for only one indicator, followed by scenarios v to vii, which show good performance for two indicators, and viii with the best scenario among all. It is important to note that the scenarios and their characteristics show a performance in a comparative manner among all the obtained VSM4S scenarios, and not in absolute terms.

After the graphical representation of the different scenarios resulting from VSM4S and their classification, the decision-maker can finally choose the one deemed most appropriate to achieve the company’s strategic objectives. It is expected that the scenario classified as fully viable (option viii in Fig. 6) will be chosen, but the purpose of VSM4S and its representation in the cube are merely decision support tools, typically used at the upper hierarchical decision levels of the manufacturing company. Finally, after deciding which scenario to implement in the company, a new VSM4S map of the future state can be developed, as exemplified in Fig. 2, representing the new performance values obtained. The map graphically reflects all the changes that will occur in the company’s production system during the year, serving as an important diagnostic and reference tool.

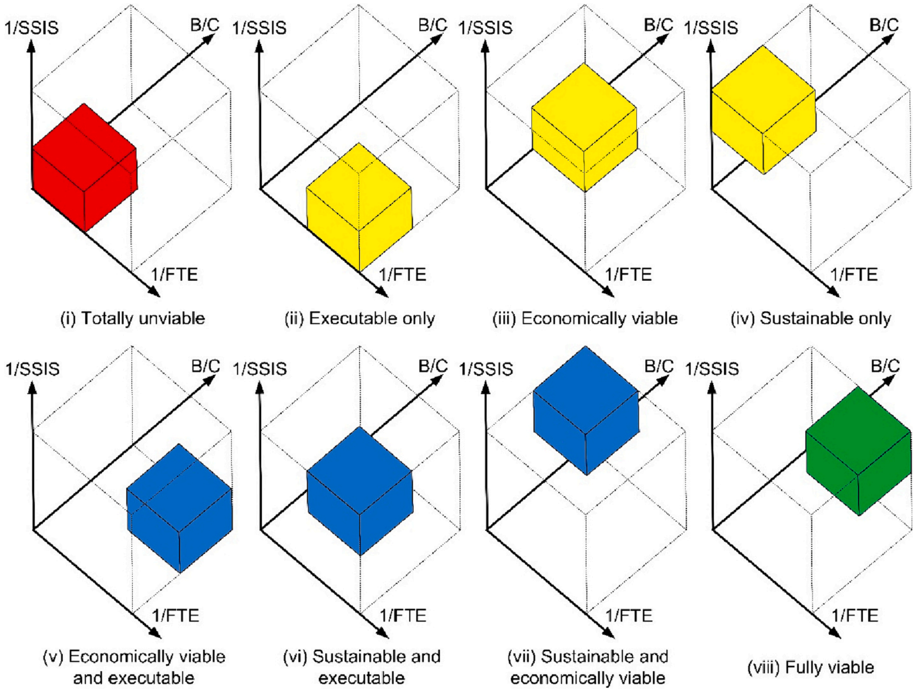
3.3. Case study description

The proposed VSM4S model, as presented in Fig. 4 and explained in detail in its subsequent sections, is applied in a hypothetical case study with the ultimate goal of demonstrating its step-by-step procedures. As one of the practical contributions of this study, it is expected that the VSM4S will be applied in manufacturing companies as a replacement for the traditional VSM, thus, presenting how to apply the model in a practical manner becomes a crucial step. It is important to emphasize that even though the case study is hypothetical and not a real case, this does not diminish the importance of the study nor its scientific consistency, as the aim is to propose the VSM4S model rather than its application in real cases; this will be the subject of future studies. Given that this is a hypothetical case study, the stages of VSM4S (Fig. 4) that require the selection of indicators feeding into the 5SEnSU, goal definition, and the establishment of Kaizen projects to achieve these goals have been assumed by the authors of this study. The chosen indicators and their magnitude order are based on the authors’ previous experience in sustainability and circular economy concepts, besides having experience on management methods in manufacturing companies and tools for quantifying environmental load such as life cycle assessment. In a real study, the VSM expert team within the company should decide on these aspects, preferably in a participatory manner, and quantify the indicators with data obtained in situ (on the factory floor).

4. Results and discussions

4.1. Applying the VSM4S in the case study

Just as with any new method proposal, applying it to case studies helps in understanding the steps to be followed, including calculations, necessary data, among other issues that would raise doubts. Although a hypothetical case (with three processes P1, P2 and P3; similar to Fig. 1) application of VSM4S is presented here to validate the model and make its procedures easier to understand, future efforts are suggested for its application in real cases to better discuss its strengths and weaknesses, besides increasing its applications in diverse manufacturing companies.



(i) Totally unviable (ii) Executable only (iii) Economically viable (iv) Sustainable only

(v) Economically viable and executable (vi) Sustainable and executable (vii) Sustainable and economically viable (viii) Fully viable

Fig. 6. The eight possible scenarios for the 5SEnSU future-state VSM4S based on sustainability indicators (SSIS), financial return (B/C Ratio), and resource utilization for project implementation (FTE).

After the team of experts has defined the scope (spatial and temporal boundaries) in which the VSM4S will be applied and the indicators that will be calculated to feed into the 5SEnSU, the process of inventory development and indicator calculation begins using primary data obtained on the factory floor. Mass and energy balances are important in this stage of quantifying indicators to ensure data consistency. Table 3 presents the selected indicators to illustrate the application of VSM4S in the hypothetical case, where two indicators were chosen for each sector of the 5SEnSU model, totaling ten indicators. All indicators are quantified for each of the three processes (P1, P2, and P3) in the hypothetical manufacturing company under consideration. Then, the consolidated results for each indicator are calculated, considering different criteria according to the characteristic of the indicator.

The consolidated results of the indicators in Table 3 are used to feed the multi-criteria approach of the goal programming philosophy in the 5SEnSU model. Supplementary Material A provides the automated Excel® spreadsheet with the goal programming considered in this example of VSM4S application. By using the goals and objectives for each indicator as presented in Table 4, the SSIS can be calculated for the current state, resulting in a value of 35.56, as available in Supplementary Material A. The punishments considered are those suggested earlier in the text of this study (4.9, 2.3, and 1.8 for the social, environmental, and economic dimensions), and the weights of importance are considered equal to one for all sectors of 5SEnSU. As discussed previously, the goals of 5SEnSU should be established through a participatory approach involving different experts and working groups and based on the strategic planning of the manufacturing company.

Next, Kaizen projects are developed by the team of experts using the manufacturing company's goals as a reference. For this hypothetical case study, four different scenarios are assumed, as shown in Table 4. Each scenario has different individual values for each of the ten indicators considered in VSM4S, and consequently, different consolidated values. The consolidated values of the indicators for each scenario, as well as their goals and objectives used in the 5SEnSU model (which are the same as those used for the current state), are used in the multi-criteria approach (Supplementary Material A) to calculate the SSIS for each future-state scenario. Table 5 presents, in addition to the SSIS for each established scenario, their respective B/C ratio and FTE values (both chosen randomly for didactic purposes in the application of VSM4S). Finally, all the SSIS, B/C, and FTE indicators in the sample of four scenarios are normalized and interpreted according to the graphical representation of the Cube.

According to Table 5, each scenario has a different overall performance, as interpreted in the Cube. In order of best to worst overall performance among the evaluated scenarios, none were able to achieved good performance for all three indicators. Under this criterion, scenarios 2 (sustainable and economically viable) and 3 (economically viable and executable) have similar performance, with both achieving good performance for two indicators. Nevertheless, both scenarios exhibit different performances regarding environmental, economic, and social aspects. Scenario 1 (sustainable only) and 4 (economically viable) achieved good performance for only one indicator, albeit under different focuses, including environmental and economic. At this point, the final diagnosis provided by VSM4S (Table 5) is delivered to the decision-maker in the manufacturing company so that the scenario deemed most suitable for the company's established strategies can be chosen and implemented. It is worth noting that if traditional VSM were being considered instead of VSM4S, Scenarios 3 or 4 would likely receive priority, as only economic and operational aspects would be considered in the decision. However, VSM4S provides a holistic view of sustainability included in the decision, as represented by the SSIS indicator.

4.2. Strengths and weaknesses of the proposed model

While sustainability initiatives have been on the rise, they have been rarely applied in manufacturing companies due to several barriers that hinder the adoption of these practices. In a literature review on the subject conducted by Hariyani and Mishra (2022), which considered 545 scientific papers, the authors identified 31 existing barriers to sustainability practices in manufacturing companies. The top-five quoted barriers include: 1st, lack of employee awareness, training, education, and rewards; 2nd, low commitment from top management due to low awareness or a negative attitude towards sustainable manufacturing; 3rd, lack of availability of information, communication, and up-to-date data; 4th, poor partnerships; 5th, lack of leadership. The VSM4S proposed in this study has a potential to overcome some of these barriers, as it provides some adaptions on the traditional VSM, which is already well disseminated and known in manufacturing companies. The steps for implementing the procedures required data, methods of calculation, and representation of the results, which can be considered strengths of the VSM4S.

Focusing on the automotive industry, Gohoungodji et al. (2020) discussed that the main barriers to implementing sustainable innovation in the industry are related to information, technology, organizational barriers, laws, and regulations, emphasizing that behavior and resource availability are the main drivers. Similar findings were obtained in different studies, including Mahmood et al. (2019) and Gaikwad et al. (2020), which examined motivators and barriers to the adoption of sustainability practices in small and medium-sized Pakistan and Indian companies, and Ali et al. (2020), who identified barriers to the implementation of Lean Six Sigma in supply chains. In these three studies, the authors identified that the main barriers to implementing sustainability projects in manufacturing companies consist of a lack of commitment from top management, lack of resources, lack of awareness, and motivation for adopting sustainability practices. To drive sustainability practices in small and medium-sized enterprises, the authors emphasize that government pressure and awareness among top managers of companies are fundamental aspects. According to Antomarioni et al. (2020),

Table 3

Chosen indicators, their quantification for each industrial process, and their consolidated values for the hypothetical case study. Numbers correspond to the current-state for VSM4S for one-year period in average.

Chosen indicators	Industrial process			Consolidated values	Criteria
	P1	P2	P3		
K11, Embodied energy (MJeq./unit)	9.70E−07	1.15E−06	1.00E−06	3.12E−06	Total
K12, Electricity demand (kWh/unit)	1.10E−05	1.61E−05	1.01E−05	3.72E−05	Total
K21, Global warming (kgCO2eq./unit)	2.62E−06	2.62E−06	2.62E−06	7.85E−06	Total
K22, Acidification (kgSO2eq./unit)	3.50E−09	4.10E−09	6.20E−09	1.38E−08	Total
K31, Overall efficiency - OEE (%)	82.00	77.00	79.00	77.00	Lowest value
K32, Lead time (h)	1240	1900	1440	4580	Total
K41, Unemployment rate (%)	6.00	3.00	4.00	13.00	Total
K42, Average salary (BRL/month)	1045	1045	1045	1045	Same value
K51, Lost time accident rate (%)	1.50	0.50	1.00	3.00	Total
K52, Absenteeism index (%)	2.00	1.50	1.50	5.00	Total

Unit = one unit produced; BRL = Brazilian Reais (currency).

Table 4

Consolidated values of indicators for the four scenarios established according to the Kaizen projects. Numbers correspond to the future-state for VSM4S. Both consolidate values and 5SEnSU goals are hypothetical values based on the consolidated values of Table 3.

Chosen indicators	Consolidated values for indicators established according to different Kaizen projects				5SEnSU	
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Goal	Objective
K11, Embodied energy (MJeq./unit)	3.20E−06	3.08E−06	3.15E−06	3.24E−06	3.00E−06	Minimize
K12, Electricity demand (kWh/unit)	3.20E−05	3.42E−05	3.55E−05	3.00E−05	3.90E−06	Minimize
K21, Global warming (kgCO2eq./unit)	7.00E−06	7.55E−06	7.22E−06	7.85E−06	7.00E−07	Minimize
K22, Acidification (kgSO2eq./unit)	1.48E−08	1.28E−08	1.60E−08	1.80E−08	1.10E−09	Minimize
K31, Overall efficiency - OEE (%)	80.00	90.00	79.00	74.00	90.00	Maximize
K32, Lead time (h)	4200	4000	4225	4500	3800	Minimize
K41, Unemployment rate (%)	12.00	12.00	11.50	10.80	10	Minimize
K42, Average salary (BRL/month)	1070	1020	1030	1055	1090	Maximize
K51, Lost time accident rate (%)	2.00	2.50	1.10	1.20	0,80	Minimize
K52, Absenteeism index (%)	3.00	2.00	3.00	2.20	1,80	Minimize

Unit = one unit produced; BRL = Brazilian Reais (currency).

Table 5

Overall performance for the four evaluated scenarios and their interpretation by the CUBE. Numbers correspond to the future-state for VSM4S.

VSM4S future-state	SSIS[a]	B/C[b]	FTE[b]	Interpretation by the CUBE
Scenario 1	31.33 [0.79]	1.00 [0.00]	5.00 [0.40]	Sustainable only
Scenario 2	30.77 [1.00]	2.00 [0.50]	8.00 [0.06]	Sustainable and economically viable
Scenario 3	32.49 [0.36]	2.50 [0.75]	3.00 [1.00]	Economically viable and executable
Scenario 4	33.55 [0.00]	3.00 [1.00]	9.00 [0.00]	Economically viable

Numbers in brackets are normalized according to sample of four scenarios and considering the normalization method ‘max-min’ as described within main text. Important to remind that normalized SSIS and FTE are represented as 1/SSIS and 1/FTE to indicate ‘higher the best’ performance.

[a] SSIS values obtained after running the goal programing as available in the Excel® file of Supplementary Material A based on values of Table 4.

[b] B/C and FTE are hypothetical values randomly chosen.

the higher the managerial position, the lower the direct involvement in improvement projects, as well as the direct perception of the success or failure of the implemented improvement project. Thus, future studies should investigate the causes of top management's lack of commitment to sustainability aspects. It is understood that the VSM4S proposed in this study could overcome many of these presented barriers, whether through the concepts, methods, and tools used, which are already well-known and applied by companies, but it is essential for the practice of production flow mapping to become a common and recognized practice by top management of companies. For example, the goals set in VSM4S need to be aligned with strategic indicators, with active participation from highly experienced personnel from different areas and hierarchies of the company. Kaizen projects should be widely discussed to establish plausible scenarios, where the chosen scenario must be implemented with due rigor regarding the defined deadlines and with a focus on the pre-established objectives for the VSM4S of the future state.

As presented earlier, various efforts have been made to modify the traditional VSM and make it more aligned with sustainability concepts (Salvador et al., 2021; Garza-Reyes et al., 2018; Cheung et al., 2017; among others). Although important attempts, most studies have proposed non-integrated approaches between economic, social, and environmental capitals, or have discussed about sustainability without presenting models epistemologically rooted in science. Therefore, a differentiator of the VSM4S proposal is to overcome these two identified problems because, in addition to discussing sustainability based on the 5SEnSU conceptual model, all three economic, social, and environmental capitals are considered simultaneously under a multicriteria approach, making results more comprehensive. Additionally, the inclusion of the cube approach to assist in decision-making can be understood as a differential since the decision-maker generally needs to align the variables of sustainability, economics, and labor availability for an effective strategic decision in pursuit of more sustainable manufacturing companies.

For companies that need to go through a reengineering process, VSM4S also becomes an important tool to be considered in the Business Process Redesign (BPR) phase when it comes to manufacturing issues. It is important to highlight that as it should happen with traditional VSM, the success of applying VSM4S requires a systemic perspective, where different experts within the company work together in an integrated manner, so that everyone can see the causes of problems systematically, propose joint solutions, and feel like an integral part of the manufacturing company. While it is understood that difficulties may arise in implementing VSM4S in its first attempt, it is also understood that all potential applicability issues will be overcome in the following years, and the advantages of VSM4S will be compensatory.

Applying the VSM4S will require efforts from work teams with expertise in different aspects of manufacturing, all led by the sustainability manager figure that possess a systemic background and capable of easily applying various quantitative approaches to sustainability quantification, as well as managing teams. The reliance on a large amount of social, economic, and environmental manufacturing data may be considered a weakness of VSM4S. On the other hand, if manufacturing truly aims to become more sustainable, there is hardly an operationally easy path, necessitating a shift from the traditional production paradigm, a change in the mindset of managers and workers. Without this profound change, significant improvements in manufacturing sustainability are unlikely to be achieved. This informational aspect is crucial for changes in the status quo or business-as-usual, which require certain initial efforts, including monetary aspects, personal motivations, and other cultural factors. VSM4S aids the company in better understanding itself, how it operates from a systemic perspective, its internal and external relationships including material, energy, information, and monetary flows within an open system, to identify points of change for improvement.

Future efforts will be directed towards assessing the advantages and disadvantages of VSM4S in comparison to traditional VSM. To achieve this, a set of parameters such as complexity, data availability, team allocation, among others, will be taken into consideration, with manufacturing experts as the target audience. This evaluation is likely to be conducted through questionnaires administered to these experts. Additionally, the application of VSM4S will be implemented in real case studies to facilitate discussions regarding its practical application.

5. Conclusion

Although acknowledging that the operational applicability of the proposed Value Stream Mapping for Sustainability (VSM4S) in this study needs further investigation, it successfully incorporates sustainability aspects into the traditional VSM, which typically focuses solely on economic factors. Integrating the concept of sustainability and its quantification into existing, accepted, and widely used management tools by manufacturers becomes a powerful strategy for driving decisions in manufacturing towards greater sustainability in business, thereby contributing to achieving greater sustainability beyond the company's borders as well. The distinctive feature and significant advantage of VSM4S compared to other alternatives lie in its approach not as a new tool, but rather in proposing alterations - such as models, definitions, and scientifically rooted procedures - within a classic tool used by manufacturers.

To present step-by-step how to operationally apply the VSM4S, a hypothetical case study was presented to highlight details on establishing choices and criteria when applying the model in real manufacturing scenarios. Applying VSM4S could potentially yield a series of benefits beyond providing the company with self-knowledge regarding its potential for sustainability, such as accessing bank credit lines with lower interest rates domestically and internationally, avoiding so-called 'greenwashing', becoming eligible to participate in national projects exclusive to more sustainable companies, enhancing competitiveness compared to other firms, as well as improving their image and expanding in an increasingly demanding market focused on quality and sustainability. Given that manufacturers play a prominent role as agents that demand and transform a large amount of materials and energy, exerting significant pressure on the natural environment, sustainability in companies proves to be a fundamental piece in the complex puzzle of the United Nations' sustainable development goals.

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CRediT authorship contribution statement

Euclides Serafim Silva: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Feni Agostinho:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Cecília M.V.B. Almeida:** Writing – review & editing, Visualization, Methodology. **Gengyuan Liu:** Writing – review & editing. **Biagio F. Giannetti:** Writing – review & editing, Visualization.

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.

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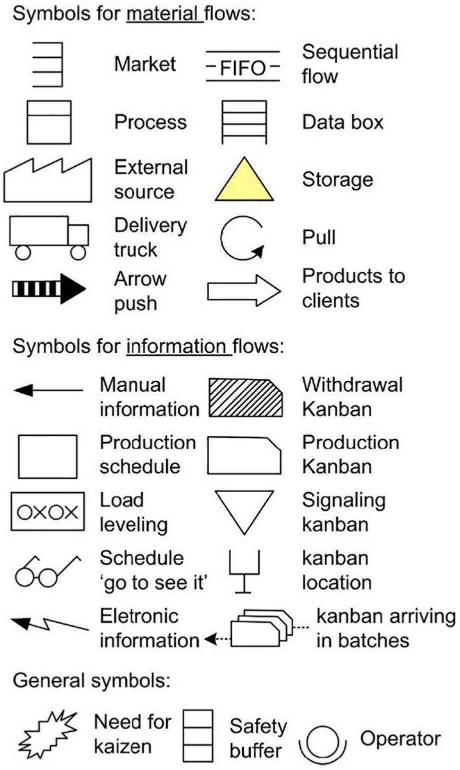
Appendix A. Symbols used in the preparation of the Value Stream Mapping (VSM). Source: Rother and Shook, 1999



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