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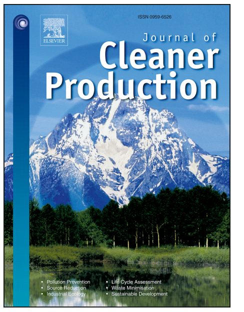

Integrating sustainability indicators and Lean Manufacturing to assess manufacturing processes: Application case studies in Brazilian industry

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Abstract

Operation management models have been developed according to changes in society's demands, such as better working conditions, clean production, recyclable and reusable products, and improving social conditions. Thus, new challenges in developing sustainable management models, particularly for manufacturing processes, have emerged. Lean Manufacturing and Value Stream Mapping (VSM) have been widely used to develop manufacturing processes without wastes in the production flow. However, current indicators of the VSM tool have not identified the economic, social and environmental factors. This work aims to propose a conceptual method to integrate a new group of sustainability indicators into the VSM tool to assess manufacturing processes. The development of sustainability indicators was performed through analysis of the assessment models of sustainability and sustainability indicators in the period of 2009 to 2014. The method was applied in three case studies, and the results demonstrated that the proposed method identified different levels of sustainability of manufacturing processes and thus enabled the development of improved scenarios. In this sense, the results contributed to the literature with the proposition of new sustainability indicators related to the manufacturing process. The case studies enabled evaluation of the interaction of a new group of sustainability indicators in different manufacturing processes.

Keywords: Sustainability Indicators; Lean Manufacturing; Manufacturing Process; Value Stream Mapping; Sustainable Operations

1. Introduction

The characteristics of operation management models have evolved over a period to adapt to the new challenges of society. In the beginning of the twentieth century, the expansion of industries resulted in management models based on standard operations and the analysis of time and methods (Cheng *et al.*, 2011). In the post-World War II period, the growth of consumer demand resulted in the improvement of quality and best practices in operation management (Voss *et al.*, 2002). At the end of the twentieth century, the growth of competition and diversity of consumer demand due to globalization resulted in manufacturing processes managed according to quality, cost, delivery, flexibility, speed and reliability indicators (Chowdary and George, 2012; Kim *et al.*, 2015).

According to Moyano-Fuentes and Sacristan-Díaz (2012), Lean Manufacturing (LM) has been widely applied in the management of manufacturing processes. To Ohno (1988), LM aimed for the elimination of activities and procedures that do not add value to the final product. Therefore, Chowdary and George (2012) enhanced the operational improvement in a company due to the implementation of LM practices. Reductions of waiting time, cycle time and inventory were among the improvements to manufacturing processes. Chen *et al.* (2010) presented a case study of the LM implementation in a factory in the USA. The use of the VSM tool resulted in reduced inventory and rework levels. In addition to the benefits of the production flow, Dues *et al.* (2013) commented that the use of LM tools also maximizes the gains in environmental and social areas of the manufacturing process.

Because of this, many authors seek the integration of sustainability indicators into VSM. Paju *et al.* (2010) integrated Life Cycle Assessment (LCA) and Discrete Event Simulation (DES) into VSM. Faulkner and Badurdeen (2014) utilized a group of sustainability indicators integrated into VSM to assess the sustainability level in companies with different characteristics in relation to the production volumes and product varieties. The model used consumption indicators (water, energy and raw materials), noise level and ergonomic analysis of the workplace as sustainability indicators. Kuhlang *et al.* (2011) used area and transportation (time and distance) indicators via VSM to evaluate and develop improvement scenarios for manufacturing processes. Lee *et al.* (2012) and Kumaraguru *et al.* (2014) analysed changes in production systems and services towards sustainable solutions, and they highlighted the need to develop methods to measure the levels of sustainability of manufacturing processes.

Thus, it can be noted that, despite the evolution of manufacturing systems towards sustainability, there are no standardized methods for assessing sustainability in manufacturing processes and no consensus on which indicators should be used. Ghadimi *et al.* (2012) stated that sustainable production has become an important issue among manufacturing organizations, and several methods have been developed to assess the corporative sustainability company level (ISO 14000 series, Social Accountability 8000 standard and GRI Sustainability guidelines). However, there is an opportunity to develop methods for assessing sustainability in manufacturing processes that consider the three dimensions of sustainability (economic, social and environmental).

This article aims to develop and apply a method that integrates a new group of sustainability indicators into VSM to assess manufacturing processes in Brazilian industry. The sustainability context of application in manufacturing processes in Brazilian industry is relevant to the literature due to its position as a global production centre composed of numerous multinational companies (Abele *et al.*, 2008). Brazil is also part of a group of developing nations (BRICS) and the most economically active in Latin America (Jabbour et al., 2015; Echegaray, 2016).

The new group of sustainability indicators allowed for analysis of the manufacturing process from the perspective of lean manufacturing associated with the three dimensions of sustainability. The integration of economic indicators resulted in the insertion of the operations and inventory costs into the assessment of the manufacturing process. The Takt Cost indicator determined the economic sustainability level of the manufacturing process and cost constraint operation. The Takt Cost can be obtained through analysis of the external factors or through analysis of the cost of the operations. The integration of social and environmental indicators allowed for assessment of the level of sustainability. For the analysis of these indicators, reference values were used considering the area where the manufacturing process was inserted. Thus, it was possible to identify the constraint operations relative to global or regional benchmarks.

2. Lean Manufacturing and Sustainability Indicators

Lean Manufacturing stands out as a model of manufacturing process management. Taj (2008) and Eatock *et al.* (2009) defined LM as a set of concepts, principles, methods, procedures and tools geared towards improvement of the production flow by reducing waste. Among the several tools of Lean Manufacturing, VSM (Value Stream Mapping) can be highlighted since it provides a holistic view of manufacturing processes and has been one of the most used in the universe of applications of lean thinking in industrial and service companies (Lasa *et al.*, 2009). According to Rother and Shook (1999), VSM describes the information and process flow, which allows for identification of sources of waste, and thus it proposes future scenarios for improvement. McDonald *et al.* (2002) applied VSM in an engineer to order a production system to identify waste in all stages of the manufacturing process, and thus they reduced the process lead-time. Seth and Gupta (2005) utilized VSM to reduce high inventory levels and activities that do not add value to the process, and as a result, they increased the productivity of a process in the automotive industry. Lummus *et al.* (2006) applied VSM in a medical clinic to reduce the waiting times of patients, which demonstrated that VSM can be applied in different segments. VSM can be used to identify points of waste or opportunities for improvement in processes of all applications.

Thus, some studies have integrated new indicators into VSM to extend the scope of analysis. Kuhlang *et al.* (2011) proposed an extended VSM with area and transport indicators. The analysis of the extended VSM proposed by the authors allowed for development of future scenarios to improve the manufacturing process towards optimization of the production flow (Lean Manufacturing Concepts), the area used for operations and inventory (Area Indicator) and the distances and time travelled in internal logistic operations (Transport indicator).

More recently, several authors have also started considering sustainability indicators to amplify VSM comprehensiveness. Faulkner and Badurdeen (2014) developed a model of sustainable VSM (Sus-VSM) through the integration of sustainability indicators. The model uses environmental indicators related to the consumption of raw materials, water and energy. The Social indicators are related to work safety, ergonomic aspects and level of noise. The economic dimension used the same indicators as the traditional VSM, i.e., cycle time of operations that add and do not add value. Brown *et al.* (2014) applied the model developed by Faulkner and Badurdeen (2014) in three companies with different configurations of manufacturing processes (Flow Shop, Manufacturing Cells and Job Shop). The application confirmed the efficiency of the model in the development of future scenarios to reduce the consumption of water, raw materials, and energy and the level of noise in operations.

Brundtland (1987) and Clancy *et al.* (2013) defined sustainability as a group of actions taken to meet the needs of the present moment without committing to future capacity. According to Faulkner and Badurdeen (2014), sustainability is the ability to maintain profits as expected by shareholders, to manufacture without damaging the environment and to improve the quality of lives of stakeholders. Elkington (1997) defined sustainability as the balance of economic, social and environmental dimensions, known as the TBL concept (Triple Bottom Line). Strezov *et al.* (2013) emphasized that each dimension of sustainability consists of indicators to assess the sustainable performance of the company. Therefore, economic, environmental and social indicators have been inserted into sustainability management models (Searcy and Elkhawas, 2012; Schonsleben *et al.*, 2010).

According to Bartelmus (2010), economic sustainability and, consequently, its indicators are directly linked to the profitability of the company. However, environmental and social factors may enhance the sustainability due to the increased value of their image in society. Martinez-Jurado and Moyano-Fuentes (2014) stated that economic sustainability aims for decision-making in the present that will make the company prosper in the future. Roufechaei *et al.* (2014) highlighted that economic sustainability will always build on the investment ratio and its return according to the expectations of the investor. Therefore, the use of integrated economic indicators in VSM contributes to the assessment of the economic characteristics of the manufacturing process and the effectiveness of actions for sustainability. However, this integration requires detailed information regarding the cost of operations (Lee *et al.*, 2014).

Hueting (2010) defined environmental sustainability as any action that will protect vital environmental functions for future generations. Hutchins and Sutherland (2008) discussed environmental sustainability as a result of the actions of companies in relation to product lifecycle management and the integration of supply chains. Dues *et al.* (2013) analysed the relationship between Lean and Green practices in supply chain management and concluded that Lean manufacturing can serve as a catalyst for the implementation of green practices, as they both feature: Waste Reduction; People and Organisation; Lead-time Reduction; Supply Chain Relationships; KPI and Tools / Practices.

Sachs (1999) addressed the issue of social sustainability and identified several factors that influence people: social homogeneity, salary and benefits, the capacity to purchase, and stable employment. Berns *et al.* (2012) highlighted that companies may have competitive advantages with the improvement of social indicators, such as employee retention, reduced absenteeism and turnover, and improved pay and benefits. Mendiola *et al.* (2013) noted that a reduction of absenteeism results in improving the company's image and reputation in society and improving productivity. Laureani and Antony (2010) highlighted the increased turnover compared to reduced process productivity. Shah *et al.* (2012) and Coetzee *et al.* (2014) addressed motivational aspects and the absence of employee recognition, in addition to remuneration, as the main causes of increase in turnover and the consequent reduction in productivity.

To achieve sustainable processes, companies have sought to contemplate the three dimensions of TBL. However, the challenge is to define the relevant indicators for each dimension and understand how they connect with each other to achieve truly sustainable processes. Table 1 shows sustainability indicators found in the literature from 2009 to 2014.

Table 1: Literature Review regarding Sustainability Indicators (2009-2014).

Dimension	Area	Indicators	Authors
Economic Dimension	Cost Management	Costs (equipment, materials and services); Acquisition; ROI- Return on Investment	Hallgren and Olhager (2009); Aguado *et al.* (2013); Lee *et al.* (2014)
	Corporative Management	Competitiveness; Tools of Corporate Management; Strategic planning process; Market Share; Number of Recycled Material suppliers	Aguado *et al.* (2013); Sampaio *et al.* (2011); Pettersen (2009); Hajmohammad *et al.* (2012); Jabbour *et al*. (2012)
	Operational Efficiency	Cycle time; OEE; Lean manufacturing waste; Set-up time; Flexibility; Inventory and Stock; Quality of products and services; Total Quality Management (TQM)	Hajmohammad *et al.* (2012); Pettersen (2009); Lee *et al.* (2014); Hallgren and Olhager (2009); Jabbour *et al.* (2012); Sampaio *et al.* (2010)
	Products	New products; Innovation and insertion in international markets; DFMA (Design for Manufacturing and Assembly)	Jabbour et al. (2012); Junquera *et al.* (2012); Hajmohammad *et al.* (2012)
	Operating Results	Profits; Price; Operational Indicators.	Aguado *et al.* (2013); Sampaio et al. (2011)
	Suppliers	Standards for Supplier; Just-in-time; Delivery	Tseng *et al*. (2012); Hajmohammad *et al*. (2010)
	Customers	Number of complaints per customer/region; Deadline;	Sampaio *et al.* (2011); Hallgren and Olhage (2009); Jabbour *et al.* (2012)
	Infrastructure	Proximity to transportation hubs; Alternative transport availability; Availability of storage facilities; Efficient use of transport resources; Available manufacturing facilities	Sather *et al.* (2011)
Social Dimension	Economic	Salary and benefits	Jabbour *et al.* (2012); Roca and Searcy (2011); Lee *et al.* (2014)
	Satisfaction Level	Level of Employee satisfaction; Absenteeism; Turn Over	Lee *et al*. (2014); Freeman *et al.* (2010)
	Quality and Health	Health Programmes and Safety Employees; ergonomics; Noise level; Average distance travelled by employees to the company	Lee *et al*. (2014); Brown *et al.* (2014); Faulkner e Badurdden (2014); Chen *et al.* (2012); Roca and Searcy (2011);
	Human Resources	Availability of labour, skilled labour; Recruitment and selection; Hours of Training; Performance evaluation (for employees)	Daily *et al.* (2011); Roca and Searcy. (2011); Jabbour *et al.* (2012)
	Community	Corporative philanthropy; public health; community development	Roca and Searcy (2011)
Environmental Dimension	Environmental Management	Policy / Environmental Standards; Indicators and Environmental Goals; Structure Responsible for the Environment; Monitoring Biodiversity; Voluntary disclosure of information on environmental performance	Jabbour et al. (2012); Hajmohammad. *et al.* (2012); Luna *et al.* (2011); Haden *et al.* (2009); Roca and Searcy. (2011)
	Environmental Aspects	Environmental Aspects and Impacts; Supplier relationship with the environment; Company image in relation to the Environment	Pampanelli *et al.* (2014); Jabbour *et al.* (2012); Junquera *et al*. (2012); Haden *et al.* (2009); Luna *et al.* (2010)
	Responsibility	Treatment / Disposal of Waste; Consumption of hazardous materials	Jabbour *et al.* (2012); Hajmohammad *et al.* (2012)
	Consumption	Water, energy and paper	Aguado *et al.* (2013); Pampanelli *et al.* (2014); Haden *et al.* (2009); Hajmohammad *et al.* (2012); Lee *et al.* (2014); Brown *et al.* (2014)
	Product Life Cycle	Product Lifecycle analysis	Tseng et al. (2012); Jabbour *et al. (*2012)
	Recycling	3 R's (Reduce, Reuse, Recycle) Culture	Haden *et al*. (2009); Hajmohammad *et al.* (2012); Jabbour *et al.* (2012); Luna *et al*. (2011); Lee *et al.* (2014); Brown *et al.* (2014)

The economic indicators have been defined according to the specific application, but they can be gathered by similarity, such as cost management; corporative management; operational efficiency; products; operating results; suppliers; customers; and infrastructure.

The indicators of the social dimension have a wide commitment and approach labour availability in the community, level of quality of life and safety of the workplace, salary, and philanthropy. Thus, they were gathered into groups of economics; satisfaction level; quality and health; human resources; and community.

The indicators of the environmental dimension included the consumption of natural resources, management of disposal, and reuse through the recycling culture and were grouped as Environmental Management; Environmental aspects; Responsibility; Consumption; Product Lifecycle; Environment; and Recycling. Different from economic indicators, social and environmental indicators are qualitative and must be analysed by comparing with reference values in the region where the company or manufacturing system is inserted.

3. Research Method

The research method used in this work is separated into three steps. Step 1 - Develop a conceptual method of assessment of sustainable manufacturing processes. This step is separated into two distinct parts: a literature review regarding sustainable indicators (Step 1.1) and the definition of sustainability indicator groups that compose the assessment method (Step 1.2). Step 2 - Apply the assessment method in Brazilian industries. Step 3 - Analyse the improvement opportunities in the case studies. Figure 1 shows the research method, including the steps.

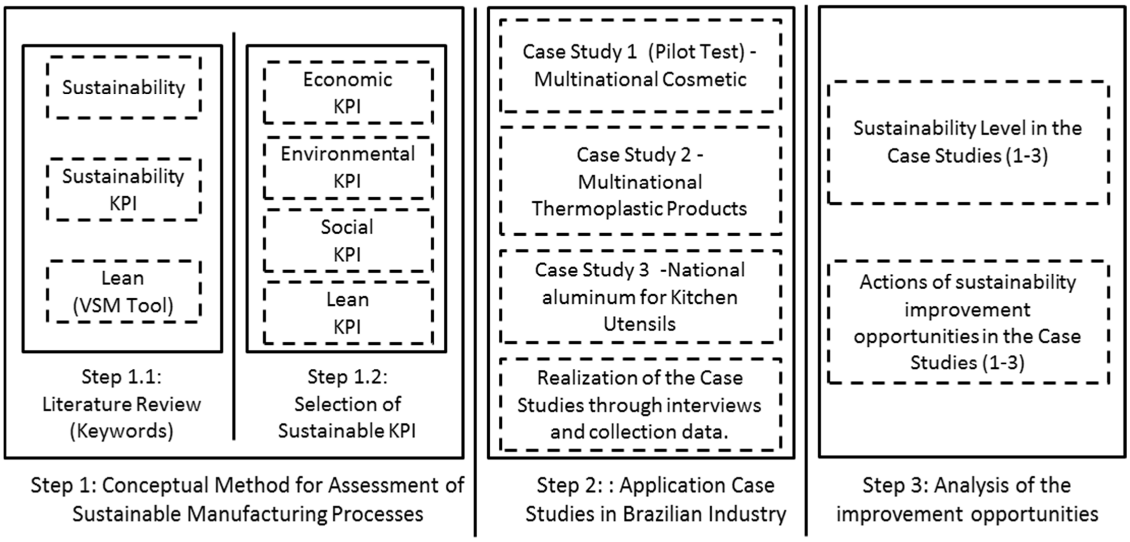

Figure 1: Research Method.

Step 1 aimed to define a new group of sustainability indicators (Economic, Environmental and Social KPIs), which were integrated into the VSM tool (Lean KPIs) to generate a conceptual method for assessing sustainability in manufacturing processes (Step 1.2). The integration of sustainability indicators in the VSM tool was based on valuation models presented by Kuhlang et al. (2011) and Faulkner and Badurdeen (2014). The selection of sustainability indicator groups was based on the concept of TBL (Triple Bottom Line) and a literature review from 2009 to 2014 considering the following keywords: Sustainability; Sustainability indicators, Lean Manufacturing and Value Stream Mapping (Step 1.1). The results of the literature review can be seen in Table 1.

To evaluate the applicability of the conceptual method of assessing sustainability in the manufacturing process, three case studies in Brazilian industries were developed. The selection of cases was performed by location criteria and senior management support of the research process, as well as to represent scenarios with different levels of sustainability in manufacturing processes. Case Study 1, considered the pilot test, was conducted in a multinational cosmetics industry that has high maturity in lean manufacturing and corporative sustainability practices (ISO 14000 series, social accountability 8000 standard and GRI sustainability guidelines). Case Studies 2 and 3 were conducted in a multinational thermoplastic products industry and an aluminium for kitchen utensils industry, respectively.

Different than what usually occurs in a VSM analysis, in which the Lean KPIs (Takt Time, OEE, Cycle Time, Workers and Work in Process) are obtained by means of observation of the manufacturing process, the application of VSM with sustainability indicators requires information that normally can be obtained in support departments of the manufacturing process, such as human resources, safety, accounting, quality and environment. Thus, the application of the case studies was carried out through observations of the manufacturing process and interviews with the other departments involved. In addition, interviews were conducted with senior management to acquire reference values for the sustainability indicators.

4. Conceptual Method for Assessment of Sustainable Manufacturing Processes

The proposed conceptual method was designed to integrate a new group of sustainability KPI with the VSM tool (Lean KPIs) to assess the manufacturing process parameters. Thus, this method does not consider the assessment of the parameters related to the supply chain, logistics supply and product lifecycle.

As stated in the research method, the new group of sustainability KPI was developed based on the TBL concept and literature review (Table 1). Therefore, this group consists of economic, social and environmental KPIs. The intent of this development was to contribute to the current sustainability assessment methods with a group of indicators that measure the parameters that influence the productivity and thereby promote the improvement of sustainability.

4.1. Economic KPIs

The economic KPIs have been developed based on the study of Eccles, Ioannou and Serafeim (2011), which defined the social and environmental dimensions as being directly associated with the payback period to be expected. However, Lubin and Esty (2010) stated that most organizations do not have full knowledge of the best metrics to measure the cost-benefits of sustainability, consequently creating barriers to the application of sustainability models.

Thus, the literature review found economic indicators in eight areas, as shown in Table 1, and considering the selection criteria, the conceptual method presented Economic KPI in three areas: cost management; operational efficiency and operating results. Table 2 shows the Economic KPIs used in the conceptual method.

Table 2: Economic KPIs used in VSM.

Economic KPI / Equation	Input Parameters	Literature Review (Area/Author - Table 1)
Operation Cost (OCo) [US$] $OCo = CT \times (DILC$+DIMC+FED) (Eq. 1)	CT - Cycle Time; DILC - Direct and Indirect Labour Costs; DIMC - Direct and Indirect Management Costs; FED - Facilities and Equipment Depreciation	Cost Management
Effective Cost (ECo) [US$] $ECo = \frac{OCo}{OEE}$ (Eq. 2)	OCo - Operation Cost; OEE - Overall Equipment Efficiency. Note: The relative ECo is determined in relation to the Takt Cost	Operational Efficiency
Stock Cost (SCo) [US$] $SCo = \begin{cases} S \times \sum_{j=n-1}^{n} ECo_j \; for \; n > 1 \\ S \times \sum_{j=0}^{n=1} RmC \quad for \; n = 1 \end{cases}$ (Eq. 3)	S - Quantity of Stock before the operations; n - number of operation; RmC - Raw Material Cost	Operational Efficiency
Target Cost Process - Takt Cost [US$]; $Takt\ Cost = \frac{\sum OCo}{OEE_{ref}}$ (Eq. 4)	OCo - Operation Cost; WCM OEE (85%). Note: The Takt Cost can also be determined by market analysis	Operating Results
Cost Cycle Efficiency (CCE) [%]; $CCE = \frac{\sum ECo}{\sum SCo}$ (Eq. 5)	ECo - Efficient Cost; SCo- Stock Cost	-
Level of Economic Sustainability (LEcS) [%] $LEcS = \frac{Takt\ Cost}{\sum ECo}$ (Eq. 6)	Takt Cost - Target Cost Process; ECo - Efficient Cost	-

The economic KPIs used the same concept of the VSM tool with respect to operations that add and do not add value for the customer. Thus, each operation of the manufacturing process presented an operation cost (OCo) that was determined by Eq. 1 and was considered as an operation that adds value. For determination of the effective operation cost (ECo), the operational efficiency through OEE (Eq. 2) was considered. The cost of inventories of raw materials, finished products and working in process (SCo) were determined according to Eq. 3, which considered reference stock cost increases over the manufacturing process due to the effective operation cost (Eco). The storage cost was not considered.

To assess the cost of the manufacturing process, the reference indicator Takt Cost (Eq. 4) was determined. This indicator was developed based on the same concept of Takt Time (Lean KPI), and it determines the cost of the operations considering the cost of the operations with respect to a world-class manufacturing (WCM) process (OEE = 85%). The Takt Cost can also be determined by market analysis, and thus it becomes a target cost considering the product market.

Considering the Takt Cost, it was possible to determine an effective relative cost (%) for each operation, which represents the share of the operation in the manufacturing process cost. This allows the determination of the bottleneck operation related to the economic dimension (shown in VSM with the Symbol "$").

After the determination of the effective cost of operations (ECo), stock cost (SCo) and Takt Cost, the sustainability of the manufacturing process in the economic dimension was assessed through the Cost Cycle Efficiency (CCE) and the Level of Economic Sustainability (LEcS) KPIs. The CCE was based on PCE (Process Cycle Efficiency) (Lean KPI), which represents a relationship between operations that add value for the customer and operations that do not add value. PCE assesses the process cycle efficiency according to the time and CCE according to the cost. Thus, the assessment of the manufacturing process through both indicators should indicate the same opportunities for improvement. The Level of Economic Sustainability (LECs) was determined according to Eq. 5, and it represents the ratio of the target cost and the total actual cost of the manufacturing process. The stock costs were not considered.

4.2. Social KPIs

The definition of a social indicator group is based on the parameters of the manufacturing process that interacts directly with employees and the community in which the industry is located. In this sense, all five areas of application found in the literature review have social indicators. Table 3 shows the Social KPIs used in the conceptual model.

Table 3: Social KPIs used in VSM.

Social KPI / Equation	Input Parameters	Literature Review (Area/Author - Table 1)
Absenteeism (Abs) [%] $Abs = \frac{NHA}{NHW}$ (Eq. 7)	NHA - Number of hours absent; NHW Number of hours worked	Satisfaction Level
Turnover (Tov) [%] $TOv = \frac{[(NLa+Nad)/2]}{NEO}$ (Eq. 8)	NLa - Number of Layoffs; Nad - Number of Admissions; NEO - Number of employees	Satisfaction Level
Accident Rate (ARa) [accident] $ARa = \frac{NA}{NEO}$ (Eq. 9)	NA - Number of accidents; NEO - Number of employees. Note: The relative ARa is inversely related to the ARa (1-ARa)	Quality and Health
Noise Level (NLe) [dB]	The relative noise level is determined in relation to a reference noise level (80 dB according to OSHA, 2008)	Quality and Health
National Production Rate (NPR) [%] $NPR = \frac{PMB}{TPr}$ (Eq. 10)	PMB - Production Made in Brazil; TPr - Total Production	Community
Salary Level (SLe)	Note - The relative SLe is determined in relation to reference SLe defined by the labour agreement categories	Economic.
Benefits/Commission/Profit (BCP) [%] $BCP = \frac{\sum(Ben+Com+Pro)}{SLe}$ (Eq. 11)	Ben - Benefits of employees; Com - Commission of employees; Pro - Profit sharing of employees; SLe - Reference salary level	Human Resources
Level of Social Sustainability - Operation (LSSo) [%] $LSSo = \frac{\sum Relative\ Social\ KPI}{7}$ (Eq. 12)		-
Level of Social Sustainability - Process (LSSp) [%] $LSSp = \frac{\sum LSSo}{NOp}$ (Eq. 13)	LSTherefore, = Level of Social Sustainability in the operation; NOp - Number of operation in the process.	-

The Absenteeism (Abs - Eq. 7) and Turnover (Tov - Eq. 8) KPIs and the Accidents Rate (Ara - Eq. 9) and Noise Level KPIs are related to the level of employee satisfaction and the conditions of the work environment, respectively. All these indicators directly affect the productivity of the manufacturing process. The salary (SLe) and financial benefits paid to workers (BCP - Eq. 11) were considered as social indicators and have also been used indirectly as economic indicators in determining the cost of the operation. The industry contribution to the community was assessed by the domestic rate used in the manufacturing process (NPR - Eq. 10). It is considered that the increase in this indicator results in social and economic development in the community that the industry is located in.

The absolute values of social indicators were obtained from manufacturing process information. However, to evaluate social indicators, reference values were determined through interviews with senior management of the industry. The relative values must range from 0-100%, and absolute values above the reference were considered 100%. Relative values below 100% represent critical indicators in the manufacturing process and were illustrated in VSM with the Symbol "↓."

After the social KPI was determined, the sustainability of the manufacturing process in the social dimension was assessed through the Level of Social Sustainability in the operation (LSTherefore, - Eq. 12) and the Level of Social Sustainability in the process (LSSp - Eq. 13) KPIs. The LSSo was determined as the average value of the relative social indicators, and the number of social indicators below the industry reference values can be used to assess critical operations in the manufacturing process. The LSSp was determined as the average value of the LSSo.

4.3. Environmental KPIs

Considering the environmental KPIs, Rockstrom *et al.* (2009) highlighted the importance of understanding the limits of natural resources for evaluating the production system. For Gavronski *et al.* (2008), companies have sought environmental certification as a way to show improved environmental performance and facilitate trade relations.

Thus, the literature review found environmental KPIs in six areas, as shown in Table 1, and considering the selection criteria, the conceptual method presented KPIs in four areas: Consumption; Responsibility; Recycling; and Environmental Management. The indicators found in the literature review in the areas of Environmental Aspects and Lifecycle were not used due to the scope restriction of the proposed method. Table 4 shows the Environmental KPIs used in the conceptual model.

Table 4: Environmental KPIs used in VSM.

Environmental KPI / Equation	Input Parameters	Literature Review (Area/Author - Table 1)
Electric Power Consumption (EPC) [w/unit]	Note: The relative EPC is determined in relation to the reference defined by the process plan.	Consumption
Water Consumption (WCo) [L/unit]	Note: The relative WCo is determined in relation to the reference defined by the process plan.	Consumption
Harmful Gases Release (HGR) [m3/unit]	Note: The relative HGR is determined in relation to the reference defined by the process plan.	Responsibility
Waste Segregation (WSe) [%] $WSe = \frac{QWS}{QWG}$ (Eq. 14)	QWS – Quantity of the Waste Segregated; QWG - Quantity of Waste Generated. Note: The relative WSe is determined in relation to the reference defined by the industry.	Responsibility
Waste with Traceable Treatment (WTT) [%] $WTT = \frac{QWTT}{QWG}$ (Eq. 15)	QWTT – Quantity of Waste with Traceable Treatment; QWG - Quantity of Waste Generated. Note: The relative WTT is determined in relation to the reference defined by the industry.	Responsibility
Green Production Rate (GPR) [%] $GPR = \frac{GRM}{QRM}$ (Eq. 16)	GRM – Quantity of green raw material; QRM - Quantity of raw material. Note: The relative GPR is determined in relation to the reference defined by the industry.	Recycling
Environmental Management System (EMS)	Note: This indicator assesses the existence of an environmental management system in the process. Thus, EMS can be 0% (there is not) or 100% (there is).	Environmental Management
Level of Environmental Sustainability - Operation (LESo) [%] $LESo = \frac{\sum Relative\ Environmental\ KPI}{7}$ (Eq. 17)		-
Level of Environmental Sustainability - Process (LSSp) [%] $LESp = \frac{\sum LESo}{NOp}$ (Eq. 18)	LSTherefore, = Level of Social Sustainability in the operation; NOp - Number of operations in the process.	-

The energy (EPC) and water (WCo) consumption KPIs have been extensively addressed in the assessment models of sustainability in terms of contributing to the economic and environmental indicators. The Harmful Gases Release (HGR), Waste Segregation (WSe - Eq. 14) and Waste with Traceable Treatment (WTT - Eq. 15) KPIs were related to the environmental responsibility of the manufacturing process. The Green Production Rate (GPR - Eq. 16) KPI aims to assess the rate of use of recycled products in the manufacturing process. Although it is not part of the scope of the proposed method, this indicator can be used to assess the supply chain. The Environmental Management System (EMS) KPI aims to identify the existence of an environmental management system in the manufacturing process.

The absolute values of environmental KPIs were obtained from the manufacturing process information. However, to evaluate environmental indicators, reference values were determined through interviews with senior management of the industry (WSe, WTT and GPR) or by the process plan (EPC, WCo and HGR). The relative values must range from 0-100%, and absolute values above the reference were considered as 100%. Relative values below 100% represent critical indicators in the manufacturing process and were illustrated in VSM with the Symbol "↓." The operations that have the highest consumption of water and energy were considered bottleneck operations in the manufacturing process and were, respectively, illustrated in VSM with the symbols "💧" and "⚡."

After the determination of the environmental KPI, the sustainability of the manufacturing process in the environmental dimension was assessed through the Level of Environmental Sustainability in the operation (LETherefore, - Eq. 17) and Level of Environmental Sustainability in the process (LESp - Eq. 18) KPIs. The LESo was determined as the average value of the relative environmental indicators, and the number of environmental indicators below the industry reference values can be used to assess critical operations in the manufacturing process. The LESp was determined as the average value of the LESo.

5. Cases Studies in Brazilian Industry

5.1. Case Study 1 (Pilot Test) - Multinational Cosmetic Industry

The conceptual method for assessment was applied in the manufacturing process of a multinational cosmetic industry that has high maturity in lean manufacturing and corporative sustainability practices. The manufacturing process can be characterized as Flow Shop, and it presents a high volume and low variety of products. The customer demand was 14,400 units per day, and the industry worked 8 hours a day. Thus, the Takt time can be considered as 2 sec. per unit. The sequence of the manufacturing process is shown in Figure 2.

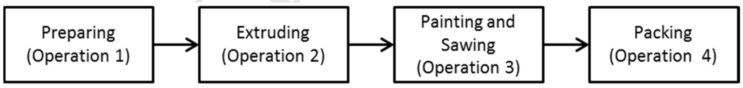

Figure 2: Cosmetic manufacturing process.

The manufacturing process information was obtained through observation of the manufacturing process and interviews with the human resources, safety, accounting, quality and environment departments. Figure 3 shows VSM with the sustainability KPI applied in the cosmetics manufacturing process.

Operations 1-4 had cycle times and OEEs equal to 0.12", 80%; 0.25 ", 80%; 0.8 ", 72%; and 0:23", 82%, respectively. The inventory in the manufacturing process was 500,000 (Raw Material), 10,000 (Work-In-Progress) and 200,000 (Finished Products). The manufacturing process was programmed as a one-piece flow.

Analysing the traditional VSM (Lean KPIs), the manufacturing process was able to meet the customer demand (Cycle Time 1-4 ≤ Takt Time) and thus can be considered sustainable. The process had a low process cycle efficiency (PCE = 0.00028%) because of the high inventory level and consequently high lead-time (17.06 days).

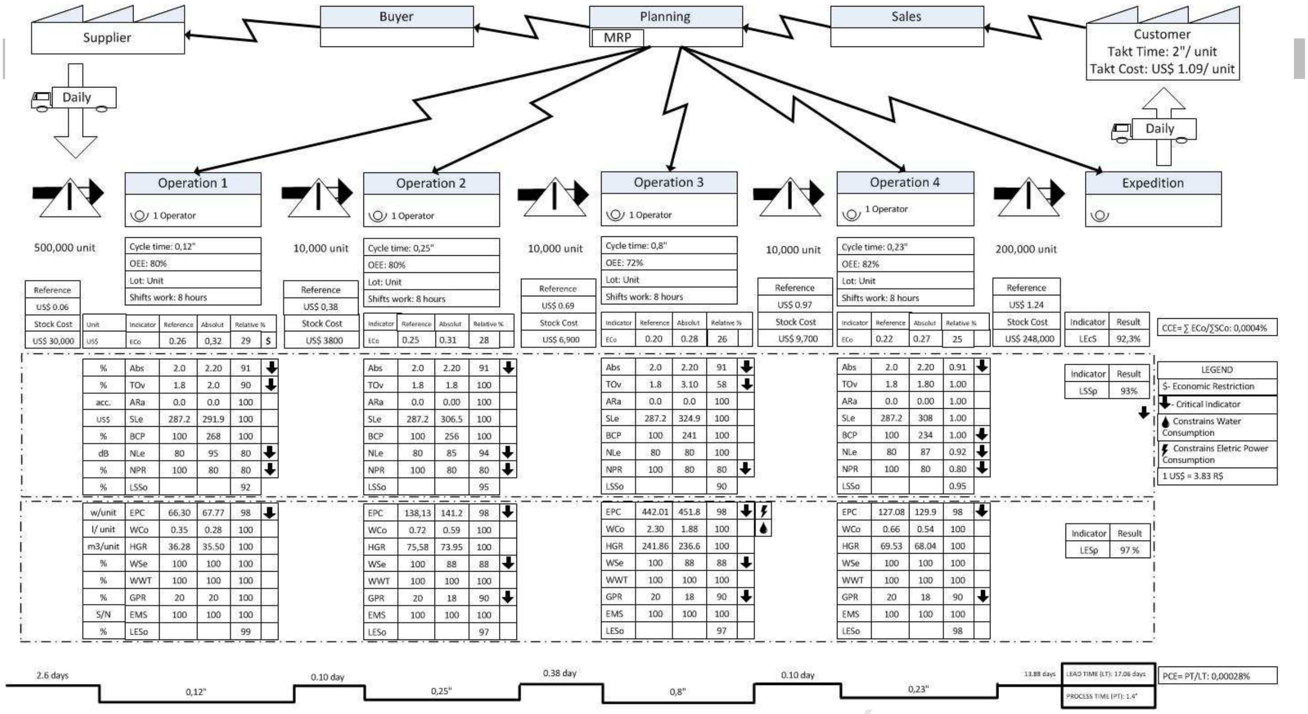

Figure 3: VSM applied in the cosmetics manufacturing process.

In the economic dimension, the process has a Takt Cost of US $ 1.09 per unit. This indicator was determined considering the cost of operations and the OEE reference (85%). The analysis of the effective cost of operations (ECo) indicated that the process cost has a low variation between operations and that operation 1 had the highest relative cost (29%). Thus, operation 1 was considered the bottleneck operation (shown in VSM with the Symbol "$"). The level of economic sustainability of the process (LEcS) was 92.3%, and thus the manufacturing process was not considered sustainable. Observing the LEcS parameters showed that the manufacturing process was operating with an effective OEE below the WCM OEE (85%).

Furthermore, the manufacturing process had low economic efficiency (CCE = 0.0004%) because of the high inventory level. The CEE assesses the cost of inventory throughout the process. This characteristic is not observed in traditional analysis of VSM (Lean KPI) because the PCE assesses the stock throughout the process, considering the time.

To assess the social and environmental dimensions, it was necessary to determine reference values for each KPIs. These values consider the company's location and the existing labour and environmental laws. They were obtained through interviews with HR (Human Resource) and production manager departments. All operations presented the same reference values for the social KPIs (Abs = 2.0%; TOV = 1.8%; ARa = 0 accidents; SLe = US$ 287.2; BCP = 100%; NLe = 80db; NPR = 100%) and the environmental KPIs (WSe= 100%, WTT = 100%, GPR = 20%; EMS = 100). For the environmental indicators EPC, WCo and HGR, the values were determined based on the theoretical consumption of operations.

The analysis of social indicators identified that the level of social sustainability of the process (LSSp) was 93%, and therefore the process was not considered sustainable. All operations have values for Absenteeism (Abs), Turnover (TOV) and National Production Rate (NPR) that are lower than the reference. Operation 3 has the lowest level of sustainability (LSTherefore, = 90%), and thus it was considered the bottleneck operation. This is mainly due to the high turnover (TOv = 3.1%) over the reference value (TOv = 1.8%).

The analysis of environmental indicators showed that operation 3 has the highest consumption of water and energy in the manufacturing process, and thus it was considered the bottleneck operation (shown, respectively, in VSM with the Symbols "💧" and "⚡"). The level of environmental sustainability of the process (LSEp) was 97%, and thus the process was not considered sustainable. All operations have higher energy consumption compared to the reference value. The GPR indicator showed critical values for operations 2, 3 and 4. The manufacturing process did not present a bottleneck operation in relation to the level of sustainability due to the low range of values between operations (97-99%).

5.2. Case Study 2 - Multinational Thermoplastic Products Industry

The case study 2 was applied in a multinational manufacturer of thermoplastic products. The manufacturing process can be characterized as Flow Shop, and it presented a high volume and low variety of products. The customer demand was 7.855 kg per day, and work was conducted 24 h per day (3 work shifts). Thus, the Takt Time was 11 sec. per kg (product). The sequence of the manufacturing process is shown in Figure 4.

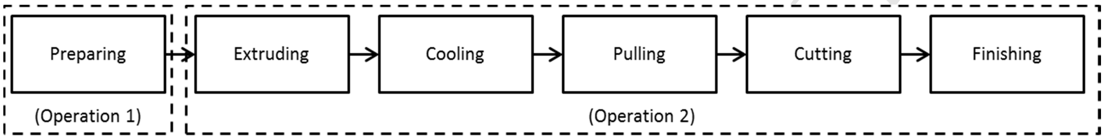

Figure 4: Thermoplastic Products manufacturing process.

Figure 5 shows VSM with the sustainability KPI applied for case study 2.

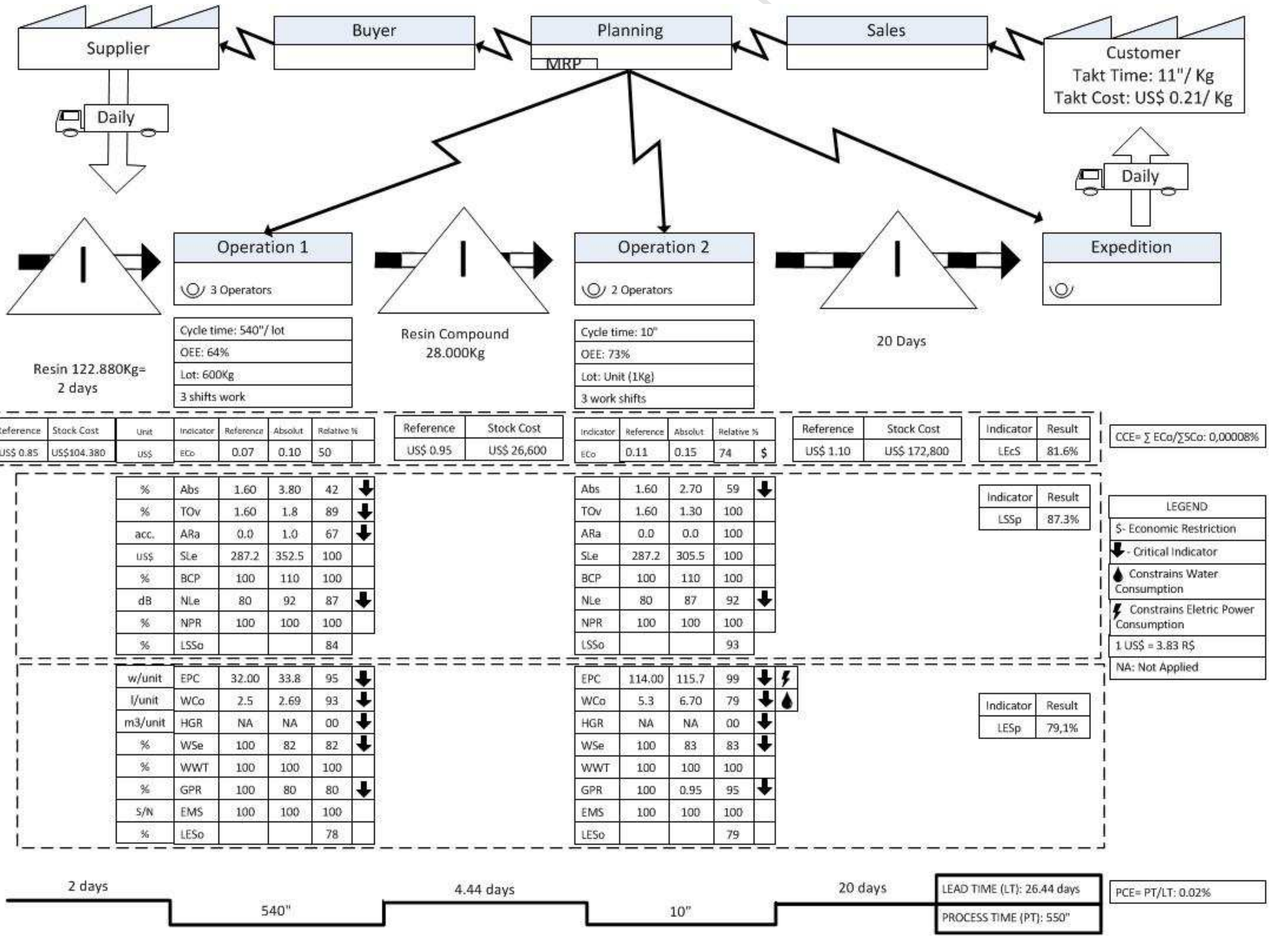

Figure 5: VSM applied in Case Study 2.

Operations 1 and 2 had cycle times and OEEs equal to 540", 64% and 10", 73%, respectively. The inventory in the manufacturing process was 122,880 kg (Raw Material), 28,000 kg (between operations) and 157,100 kg (Finished Products). Operation 1 was programmed by lot size (Lot=600 kg), and operation 2 was programmed by one-piece flow.

Analysing the traditional VSM (Lean KPIs), the manufacturing process was able to meet the customer demand and thus can be considered sustainable (Cycle Time 1-2 ≤ Takt Time). The process presented a low process cycle efficiency (PCE = 0.02%) because of the high inventory level in the process and consequently high lead-time.

In the economic dimension, the process had a Takt Cost of US $ 0.21 per kg. The analysis of the effective cost of operations (ECO) indicated that the process has a low variation between operations and that operation 2 has the highest relative cost (74%). Thus, operation 1 can be considered the bottleneck operation ("$"). The level of economic sustainability of the process (LECs) was 81.6%, and thus the manufacturing process was not considered sustainable. The manufacturing process presented too low of an economic efficiency (CCE = 0. 00008%) because of the high inventory level.

The reference indicators used to assess the social and environmental dimensions were Abs = 1.6%; TOV = 1.6%; ARa = 0 accidents; SLe = US $ 287.2; BCP = 100%; NLe = 80db; NPR = 100%, WSe = 100%, WTT = 100%, GPR = 20% and EMS = 100. For the environmental indicators EPC, WCo and HGR, the reference values were determined based on the theoretical consumption of operations.

The analysis of social indicators identified that the level of social sustainability of the process (LSSp) was 87.3%, and therefore the process was not considered sustainable. All operations have values for Absenteeism (Abs) and Noise Level (NLe) lower than those of the reference. Operation 1 has the lowest level of sustainability (LSTherefore, = 84%), and thus it is considered the bottleneck operation of the social dimension. This was mainly due to the presence of four critical social indicators (Abs, Tov, ARa and NLe).

The analysis of environmental indicators showed that operation 2 presents the highest consumption of water and energy in the manufacturing process, and thus it is considered the bottleneck operation for water consumption ("💧") and energy consumption ("⚡"). The level of environmental sustainability of the process (LSEp) was 83.8%, and thus the process was not considered sustainable. All operations presented higher energy and water consumption compared to the reference value. The GPR indicator exhibited critical values. The manufacturing process did not present a bottleneck operation in relation to the level of sustainability due to the low range of values between operations (83-84%). The manufacturing process did not control the harmful gases, and the HRC indicator was considered as not applicable (HRC=0).

5.3. Case Study 3 - Brazilian aluminium for Kitchen Utensils Industry

Case study 3 was applied in a Brazilian aluminium for kitchen utensils industry. The sequence of the manufacturing process is shown in Figure 6. The customer demand was 900 units per day, and work was conducted 8 h per day (1 work shift), which resulted in a Takt Time of 32 sec. per unit (product). The manufacturing process can be characterized as Flow Shop, and it presented a high volume and low variety of products.

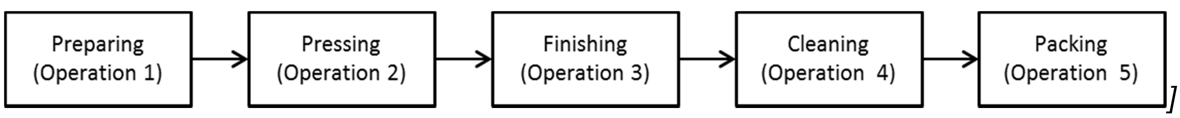

Figure 6: Aluminium for Kitchen Utensils manufacturing process.

Figure 7 shows VSM with the sustainability KPI applied in case study 3.

Operations 1-5 had cycle times and OEEs equal to 6", 62%; 20”, 55%; 24”, 55%; 4”, 72%; and 6”, 70%, respectively. The inventory in the manufacturing process was 4,860 units (Raw Material), 810 units (between operations 1 and 2), 410 units (between operations 2 and 3), 500 units (between operations 3 and 4), 810 units (between operations 4 and 5) and 17,808 units (Finished Products). The process was programmed by one-piece flow.

The manufacturing process was able to meet the customer demand (Lean KPIs) and thus can be considered sustainable (Cycle Time 1-5 ≤ Takt Time). The process presented a low cycle efficiency (PCE = 0.008%) because of the high inventory level in the process and consequent high lead-time.

In the economic dimension, the process presented a Takt Cost of US $ 1.34 per unit. The analysis of the effective cost of operations (ECo) indicated that the process has a high variation between operations and hat operation 1 has the highest relative cost (88%). Thus, it can be considered the bottleneck operation ("$"). The level of economic sustainability of the process (LEcS) was 72.2%, and thus the manufacturing process was not considered sustainable. The manufacturing process presented too low an economic efficiency (CCE = 0. 0036%) because of the high inventory level.

The reference indicators used to assess the social dimensions were Abs = 2.0%; TOv= 2.0%; ARa = 0 accidents; SLe = US$ 250; BCP = 100%; NLe = 80db; NPR = 100%. For the environmental indicator EPC, the reference values were determined based on the theoretical consumption of operations. The measurement of the water consumption system was realized by this process and because it was not possible to determine the consumption of water per operation. Thus, the indicator WCo for each operation was determined considering the average consumption. However, through the process of observation during the data collection stage, operation 4 (Cleaning) can qualitatively be considered the bottleneck operation ("💧").

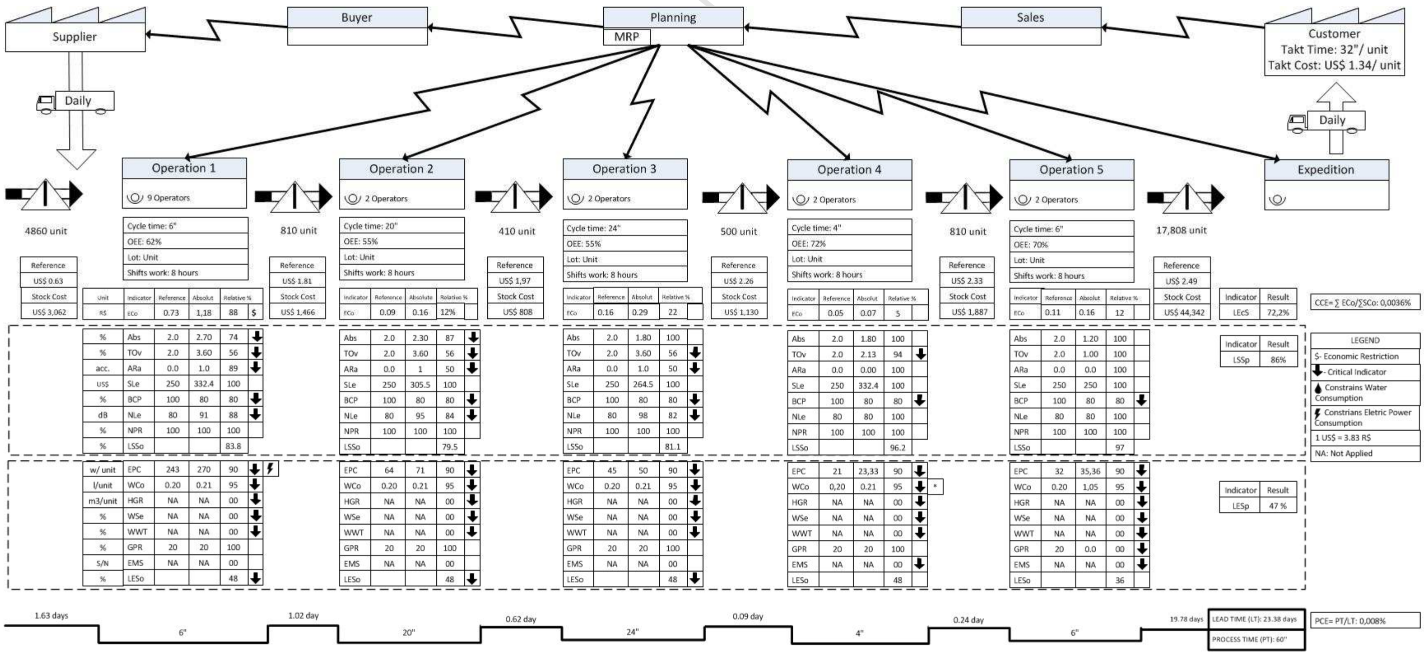

Figure 7: VSM applied in Case Study 3.

The analysis of social indicators identified that the level of social sustainability of the process (LSSp) was 86%, and therefore the process was not considered sustainable. Operations 1-3 showed the social indicators TOv, ARa, BCP and NLe in critical situations. These operations had high levels of noise and work accidents during the analysis period. Operation 2 presented the lowest level of sustainability (LSTherefore, = 79.5%), and thus it was considered the bottleneck operation of the social dimension.

The analysis of environmental indicators showed operation 1 as having the highest consumption of energy, and thus it was considered the bottleneck operation for energy consumption ("⚡"). The level of environmental sustainability of the process (LSEp) was 47%, and thus the process was not considered sustainable. The manufacturing process did not present an environmental management system and did not measure the harmful gas emissions and waste segregation, and therefore the environmental indicators HRC, WSe, WTT and EMS were considered as being equal to zero.

5.4. Improvement opportunities in the case studies

The results obtained in the sustainability assessment of the case studies are summarized in Table 5. It can be observed that the conceptual method for assessment of the manufacturing process allowed, in all cases studies, identification of the fact that the bottleneck of the process fluctuated according to the sustainability dimension. Thus, it was possible to develop improvements based on the different bottlenecks.

Table 5: Result summary of the assessment of Case studies 1-3.

Case	Lean Manufacturing		Economic Dimension			Social Dimension		Environmental Dimension			
	Lean bottleneck	PCE [%]	Economic bottleneck	LEcS [%]	CCE [%]	Social bottleneck	LSSp [%]	Water bottleneck	Energy bottleneck	Environmental bottleneck	LESp [%]
1	Operation 3	0.00028	Operation 1	92.3	0.0004	Operation 3	93.0	Operation 3	Operation 3	Operations 2-3	97.0
2	Operation 2	0.020	Operation 2	81.6	0.00008	Operation 1	87.3	Operation 2	Operation 2	Operation 1	79.1
3	Operation 3	0.008	Operation 1	72.2	0.0036	Operation 2	86.0	Not Applied	Operation 1	Operation 5	47.0

Figure 8 shows the assessment of the level of sustainability for each dimension in case studies 1-3.

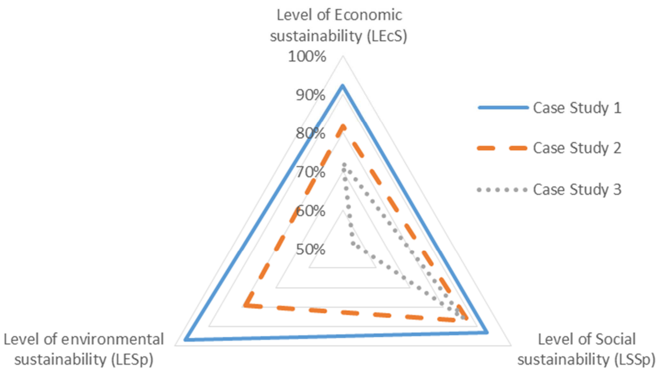

Figure 8: VSM applied in Case Study 3.

The conceptual method for assessment identified different levels of sustainability in each case study analysed. It can be seen that the sustainability level difference occurred in the economic dimension and especially in the environmental dimension.

Table 6 shows a list of improvement actions based on observed opportunities in VSM.

Table 6: Improvements Opportunities identified in Case Studies 1-3.

Action	Study Case	KPIs	Dimension	Improvement Opportunities
1	1;2;3	PCE; CCE	Lean Manufacturing; Economic Dimension	The improvement in the PCE indicator can be obtained by reducing the volume of stock during the process. The stock of raw materials and products can be reduced by increasing the frequency of deliveries (suppliers and customers) and the implementation of a pull production system. The reduction of the WIP level can obtained by balancing the time and efficiency of operations and implementation of Kanban systems.
2	1;2;3	OEE; ECo	Lean Manufacturing; Economic Dimension	The improvement OEE indicator can obtained by reduction of the defects (Six Sigma Tools), increased availability of equipment (TPM Tools), reduced setup time (SMED tools) and improvement of process cycle times (Method and Time Measurement - MTM Tools).
3	1;2;3	Eco	Economic Dimension	In addition to improving OEE (Action 2), the improvement of the indicator ECo can occur by reducing the cost of operation (OCo). The reduction of the cost operation occurs by reducing the cycle time or by reducing the direct, indirect and facilities costs.
4	1;2;3	Abs; Tov	Social Dimension	To improve the indicators Abs and Tov, it is necessary to develop actions with the department of Human Resources of the company. These actions are directly related to improving the working environment and employee motivation.
5	1;2;3	ARa; NLe	Social Dimension	To improve the indicators ARa and NLe, it is necessary to develop actions with the work safety department of the company. These actions are directly related to the reduction of accidents and noise levels in the constraints operations.
6	1	NPR	Economic Dimension	To improve the indicators NPR, it is necessary to develop suppliers in Brazil of raw materials for the cosmetics industry.
7	3	BCP	Social Dimension	To improve the indicator BCP, it is necessary to increase the level of Benefits, Commission and Profit according to the values used to determine the reference BCP.
8	3	HGR; WSe; DWT	Environmental Dimension	To improve the indicator HGR, WSe and DWT, it is necessary to implement a measuring system of harmful gas emissions and waste segregation in the manufacturing process.
9	3	EMS	Environmental Dimension	To improve the indicator EMS, it is necessary to implement an environmental management system in the manufacturing process (e.g., ISO 14,000).
10	2	EPC	Environmental Dimension	The power consumption in operation 2 occurred because of the use of electric heaters for the fusion of the raw material. Among the solutions, there is the use of thermal protection to prevent heat dissipation.
11	3	EPC	Environmental Dimension	The power consumption of operation 1 was related to the great friction of the process and low energy efficiency of equipment (old technology). Thus, the action can be directed to the renewal of equipment technology.
12	2	WCo	Environmental Dimension	The water consumption of the operation 2 was critical, using water for cooling, and waste occurs by evaporation, condensation and leaks. Thus, an opportunity for improvement could be installation of thermal insulation and realization of preventive maintenance on the pipes.
13	3	WCo	Environmental Dimension	Operation 4 used a high volume of water for cleaning, which was discarded at the end of the operation. Thus, an improvement action can be the development of a system for filtering and reuse of water.

6. Conclusions

The inclusion of the concept of sustainability in the manufacturing process through integration of Lean Manufacturing (VSM) and sustainability indicators has recently been discussed in the literature. However, the development of assessment models and indicators that effectively contribute to increasing sustainability in manufacturing processes are still in the development phase. Thus, the proposed conceptual method and the results obtained with its application in three manufacturing processes in Brazilian industry (case studies 1-3) have the main objective of contributing to this discussion and assisting in new directions for future research.

The conceptual method brings a new group of indicators associated with economic, social and environmental dimensions, which, together with the traditional indicators of VSM (Lean KPIs), seek to assess manufacturing processes and thus generate actions of continuous improvement (Kaizen) to develop sustainable manufacturing processes. The application of VSM identified the need for increased efforts in collecting data in relation to the traditional VSM. This is because information related to the economic, social and environmental dimensions are not monitored in the manufacturing process but rather by other departments, such as accounting, human resources, work safety and environmental management. The analysis of case studies allowed for identification of important characteristics that should be considered in an assessment method for improvement of the manufacturing process sustainability. All cases were sustainable from the perspective of the customer demand (Takt Time) but not sustainable in the economic, social and environmental dimensions.

The use of the Takt Cost and OEE reference contributed to important analyses in VSM and characterized the economic sustainability of the manufacturing process. Similarly, the identification of the operation with higher cost enabled the development of effective improvement actions. However, the use of stock cost (CCE) identified the same causes as the traditional indicators of VSM (PCE). The high volume of the stock in the process contributed to the increase of the lead-time and operation cost. Thus, the indicators CCE and PCE need to evolve to identify new causes or be suppressed in future applications.

The use of indicators of absenteeism and turnover for assessing the social dimension contributed to identifying distinct characteristics between the operations of the process, and although these indicators are normally general indicators of the company, the analysis allowed for the identification of critical operations. The accident and noise level indicators contributed to indicating the critical operations to safety. However, the new group of social indicators was not susceptible to assessment of workplace motivation and factors related to the development of people and the community in which the company operates.

The use of consumption indicators of operations (water and energy) to assess the environmental dimension contributed to identifying the bottleneck operations, and this allowed the development of efficient improvement actions. However, the new group of environmental indicators was not susceptible to the analysis of the product lifecycle and the characteristics of the supply chain and logistics. The identification of the bottleneck fluctuation operation from the sustainability dimension contributed to a new approach to identify opportunities for sustainability in manufacturing process improvements.

Thus, the conceptual method yielded an assessment of the sustainability of the manufacturing process based on reference values set by the company itself and thus does not allow comparisons between manufacturing processes. The development of benchmarks for the sustainability indicators should be addressed in future research. Similarly, the improvement of sustainability indicators in the direction of assessment of the workplace motivation and the development of people and the community in which the company operates (social KPIs) and of the assessment of the product life cycle and of the characteristics of supply chain (Environmental KPIs) should be other paths adopted for future research.

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