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ORIGINAL PAPER

# Life cycle assessment integrated value stream mapping framework to ensure sustainable manufacturing: a case study

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**Abstract** Sustainable manufacturing follows triple bottom line approach and requires a holistic manufacturing view across the product's total life cycle. Traditional lean manufacturing tools do not account for environmental and societal benefits. In this context, this article presents a method for value stream mapping (VSM) integrated with life-cycle assessment (LCA) for ensuring sustainable manufacture. The proposed framework is capable of visualizing and assessing manufacturing process performance from sustainability view point. Also, desired future state of performance with minimal environmental impacts also has been developed. The proposed framework has been demonstrated with an application study. The environmental impacts in four major categories are being computed and compared. The key performance measures from environment, economy, and societal perspectives were compared and percentage improvement has been computed. Discussion about selection of appropriate disposal scenario for the selected product after its use phase is made and validated. The key contribution of the study is a practical framework for LCA-integrated VSM with a desired and improved future process scenario. The scientific value of the present study is that it has contributed a new framework for VSM integrated with LCA to ensure sustainable performance. The study provides insights to practitioners to visualize process performance from traditional and environmental perspectives.

**Keywords** Lean manufacturing · Sustainable manufacturing · Value stream mapping · Life-cycle assessment · Environment · Society

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## Introduction

During the recent days, the modern manufacturing systems are expected to be lean and sustainable. Lean concepts ensure waste elimination and cost reduction (Muda and Hendry 2002). Sustainable concepts focus on the development of environmentally friendlier products and processes considering the economical and societal constraints as well (Sikdar 2007; Cockerill 2004). There exists a potential to extend lean tools for ensuring sustainable benefits. Few studies have been reported on the contest of applying lean tools for developing greener processes and strategies for environmentally benign manufacturing (Gonzalez 2014). Value stream mapping (VSM) is a fundamental lean technique to identify waste and value improvement opportunities (Rother and Shook 2003). It has been emphasized that traditional VSM framework does not account for environmental and societal performance. Hence, Faulkner and Badurdeen (2014) suggested sustainable VSM (Sus-VSM) to evaluate triple bottom line (TBL) performance of manufacturing and applied to an industry study. Though Sus-VSM indicates the sustainable performance at process level, it fails to capture environmental impacts at process level. In line with this study, the present study suggests a VSM framework integrated with life cycle analysis (LCA) to evaluate sustainable manufacturing performance. Life-cycle assessment (LCA) is an approach to assess the environmental impacts associated with a product life cycle or a service from the extraction of raw materials through to the end-of-life treatment (Global Footprint Network, GFN 2009). It is necessary for manufacturing firms to understand the environmental impacts of their products at each phase of production processes. Life cycle perspective helps manufacturers to identify possible improvements across industrial system and throughout all stages of product life cycle. Integrating LCA and VSM allows lean improvement process to focus on specific environmental improvement actions. It also provides upfront benefits in terms of monitoring the environmental impacts during lean improvement initiatives. The proposed framework amalgamates environmental assessment method and VSM to visualize and assess performance of modern manufacturing system from TBL perspective. For evaluating the environmental impacts, LCA SimaPro 8.0 was used. This software uses Eco indicator 99(I) impact assessment method which is in compliance with ISO 14044 standard which is the base for life cycle impact assessment (LCIA). One of the important requirement of ISO 14044 is, issues like land use, fine particle matter and noise must not be omitted while evaluating the environmental impacts. SimaPro 8.0 satisfies this requirement and calculates the environmental impacts as a normalized score. Using this software package, LCA study is performed and environmental impacts for each process cycle is calculated. The calculated impacts are represented under four major environmental impacts namely the carbon footprint, water eutrophication, air acidification, and total energy consumed and are being recorded in the sustainable value stream map for each process. This framework helps the firm in providing a better understanding on its sustainable performance and related environmental impacts pertaining to the current manufacturing system. After analyzing the results obtained based on the current state sustainable value stream map, the weaker areas related to sustainability can be identified and firm can make necessary actions for its improvement. The improvements can be visually tracked and recorded in the future state sustainable value stream map. To validate the applicability of the framework, a case study was conducted in an automotive component manufacturing firm. Current state value stream map was constructed and its various parameters were evaluated. Based on the sustainable value stream map, improvement actions were planned, implemented, and recorded in the future state sustainable value stream map. The current and future state illustrations provided a better insight in terms of tracking the improvements pertaining to lean and sustainable benefits. Also, two disposal scenario's for the selected product was analyzed and compared. Based on comparison of the obtained results with the deciding parameters for both the disposal scenario's, the best possible disposal method with lower impacts in terms of human health, eco system, and resources was recommended.

## Literature review

The conventional VSM was modeled to assess the value-added and non-value-added activities in industries. Various studies are available on application of conventional VSM in different sectors. Later conventional VSM was extended to capture environmental and energy performance of firms and this led to the extension of VSM to capture sustainable performance of manufacturing firms.

Culaba and Purvis (1999) described a methodology and framed a set of metrics for evaluating the environmental impact of manufacturing process using decision-making potential and knowledge-based system. They developed a knowledge-based model for sustainability assessment and applied the model in a paper manufacturing industry. Pope et al. (2004) proposed that most of the articles in the literature use environmental impact assessment and strategic environmental assessment concepts which use TBL approach for sustainability assessment. They compared TBL approach and principles-based approaches for developing sustainability criteria and concluded that principles-based approaches are more appropriate for sustainability assessment. The Organization for Economic Corporation and Development developed a comprehensive toolkit for sustainable manufacturing and primarily focussed on environmental performance of processes and products. US Environmental Protection Agency (US EPA 2007a, b) discussed about the toolkit framed by the US EPA's to track the environmental wastes using lean techniques. This tool kit helped in identifying and eliminating environmental wastes by tracking and visualizing environmental metrics namely material and water usage along with conventional VSM metrics. This toolkit failed to include energy consumption metric in VSM. Subsequently, US EPA created another toolkit which adds energy consumption metric with the existing environmental metrics in VSM which helped in tracking energy flow and consumption. However, both the tools failed to include societal metrics and emphasized more on inclusion of environmental and energy consumption metrics in conventional VSM. UNEP (2010) provided guidelines for social LCA which includes the societal aspects in performing the LCA study. The guidelines provided a deeper insight on sustainable development aspects and human wellbeing, thus creating a socio-economic LCA. Torres and Gati (2009) developed a managerial tool to align economic and environmental aspects in production process by applying VSM strategy. The tool was named as environmental VSM (EVSM) and was validated with a case study.

Paju et al. (2010) developed a methodology named sustainable manufacturing mapping (SMM) by combining discrete event simulation (DES) and life-cycle analysis (LCA) along with traditional VSM. They also identified sustainable manufacturing indicators and modeled current and future state process maps to assess the sustainable performance of manufacturing organizations. Kuriger and Chen (2011) modeled an assessment tool integrating environmental and energy metrics with VSM to evaluate the sustainability of manufacturing firms. This tool captures only the energy consumption for processes and fails to capture energy consumed for transportation. Faulkner et al. (2012) developed a methodology for Sus-VSM to capture economic, environmental, and societal sustainability of manufacturing firms. They also identified suitable metrics and visual symbols to develop Sus-VSM and conducted a study at satellite television dishes manufacturing firm. Brown et al. (2014) extended the conventional VSM and incorporated the metrics for sustainability and created a Sus-VSM. The applicability of the model was demonstrated using three case studies and the results are summarized for each case. Mayyas et al. (2012) developed a sustainability measurement model which emphasized an eco-material selection approach based on a set of quantifiable measures. They used principal component analysis as a scoring tool which is mapped against preference selection index. These tools helped in achieving a selection scheme to balance technological, societal, economic, and ecological constraints in designing automobile bodies. Singh et al. (2013) described the need to evaluate sustainable performance of automotive organizations and proposed a set of key performance indicators (KPI's) comprising 3 factors, 9 dimensions, and 41 sub-dimensions. They developed a questionnaire based on KPI's and mentioned that in future, a sustainability assessment tool need to be developed to assess economic, environmental, and societal aspects of automotive organizations. Bare (2014) proposed that sustainability assessments are necessary to support decisions that have the potential to influence sustainability from a variety of perspectives, including industrial, regional, national, and global. He also proposed that LCA's must be supported with more site-specific tools that can more appropriately address issues of land use and water use. Shojaeipour (2015) developed an automated evaluation tool based on environmental standards for identifying and quantifying the environmental impacts of manufacturing processes. The tool was developed considering three main factors namely emission, waste production, and hazardous materials to arrive at evaluating the manufacturing process.

### Research gap

Based on the literature analysis, it has been identified that most research studies consider only environment and energy metrics for evaluating sustainability neglecting the societal dimension. The model proposed by Faulkner and Badurdeen (2014) considered the societal dimension in evaluating the sustainability. Paju et al. (2010) attempted to integrate LCA into VSM framework for ensuring sustainability. It has also been identified that no attempt was made in constructing the desired future state for the current manufacturing system from sustainability viewpoint. The present study creates an LCA-integrated VSM framework which includes environmental impacts and cost dimensions in evaluating sustainability considering all three sustainability dimensions, i.e., environment, economy, and society. Also the future state map was derived for the current manufacturing system after implementing the improvement actions.

## Methods

VSM is an effective tool to analyze and improve the flow of materials and information within an organization. It also helps in identifying the improvement opportunities to eliminate wastes that prevail in the manufacturing environment. The conventional VSM provides a pictorial representation of the production system using standard symbols to map material and information flow. Conventional VSM can be extended to Sus-VSM by incorporating suitable metrics that satisfies sustainability needs. This section discusses the identification of appropriate sustainable metrics and aids to develop a comprehensive Sus-VSM, which also maps firm's economic, environmental, and societal performance.

### Sustainable manufacturing metrics

Sustainable manufacturing metrics are used to evaluate the performance of a firm from economic, environmental, and societal perspective to generate sustainable products using sustainable processes. The sustainable manufacturing metrics used in Sus-VSM are selected based on contribution of sustainability drivers toward the manufacturing processes. Researchers have proposed various sustainability models to assess the performance of manufacturing firms. However, very few studies report on sustainability evaluation at process level. Based on the review conducted, sustainability metrics must be selected in such a way that evaluation of all three sustainability drivers, namely environment, economy, and society is being performed. The selected metrics must be relevant to the industry where the study is to be conducted and all metrics should fit in a map to visually depict the performance state. In this study, selected sustainable metrics are more relevant in evaluating a manufacturing firm and further more metrics can be added or removed based on the type of industry sector

Table 1 Selected sustainability metrics

| Categories | Sustainability metrics | Measurement units | Sources |
|---|---|---|---|
| Environment | Carbon footprint | mPt | Proposed |
| | Water eutrophication | mPt | Proposed |
| | Air acidification | mPt | Proposed |
| | Water consumption | Liters (l) | Torres and Gati (2009) |
| Economy | Value-added time | Minutes (min) | Rother and Shook (1999) |
| | No value-added time | Minutes (min) | Rother and Shook (1999) |
| | Value-added cost | Rupees (INR) | Abuthakeer et al. (2010) |
| | No value-added cost | Rupees (INR) | Abuthakeer et al. (2010) |
| | Raw material consumption | Kilograms (kg) | Faulkner and Badurdeen (2014) |
| | Power consumption | Kilo watt hour (kWh) | Kuriger and Chen (2010), US EPA (2007b) |
| | Total energy consumption | mPt | Proposed |
| | Oil and coolant consumption | Liters (l) | Faulkner and Badurdeen (2014) |
| Society | Physical load index | NA | Hollmann et al. (1999), Faulkner and Badurdeen (2014) |
| | Work environmental risks | NA | US EPA (2007a), Faulkner and Badurdeen (2014) |
| | Noise level | dB | OSHA (2008), Faulkner and Badurdeen (2014) |

where the study is to be conducted. The sustainability metrics selected for this study are shown in Table 1.

*Metrics concerned with environmental dimension*

The environmental performance of manufacturing firms is evaluated by applying environmental metrics. The choice of selecting the metrics depends on the firm's manufacturing processes. The use of renewable and non-renewable resources must be taken into account and its consumption must be mapped. Based on this, the metrics such as raw material consumption, process water consumption, and energy consumption are included in the Sus-VSM.

*Metrics concerned with economic dimension*

Economic metrics ensure that economic growth of manufacturing maintains a healthy-balanced ecosystem by considering associated cost aspects. For attaining this, a better orchestrated use of resources and skills must be adopted to minimize cost factors. A cost line is being included in Sus-VSM to find the VA and NVA costs. Inclusion of cost line makes the firm to understand about their total manufacturing costs and creates opportunities to plan for improvement actions to minimize them. Apart from VA and NVA costs, the potential savings observed after reducing material consumption and power consumption is also included in this metric.

*Metrics concerned with societal dimension*

It is necessary to evaluate the impact on societal environment considering all employees and personnel involved during the manufacture of product. Potential risks pertaining to employee health and safety must be properly monitored and measured frequently. Further societal metrics are separated into two categories, namely metrics to assess physical work and metrics to asses work environment. Societal metrics serve as a useful indicator to evaluate the working conditions and to ensure employee safety. Sus-VSM assesses both the prescribed metrics, and further improvements can be planned based on assessment results.

## Description on life-cycle assessment

The Industrial Revolution transformed society and its interaction with the environment increasing the use of natural resources and the pace of development of new products and processes (Young et al. 1997). LCA is an environmental assessment tool that investigates potential environmental impacts of products and services through the whole life cycle from cradle to grave. The environmental impacts are assessed for all stages of a product from raw material extraction through materials processing, manufacture, distribution, use, repair, and maintenance to disposal or recycling. LCIA identifies and evaluates the amount and significance of potential environmental impacts and if they are in accordance with ISO standards (Vinodh et al. 2012). An LCA study consists of four main phases namely goal and scope of study, life cycle inventory (LCI), LCIA, and interpretation. Goal and scope phase defines the context of the study and includes the technical details needed for the study. LCI analysis involves creating an inventory of flows. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water. LCIA phase is aimed at evaluating the

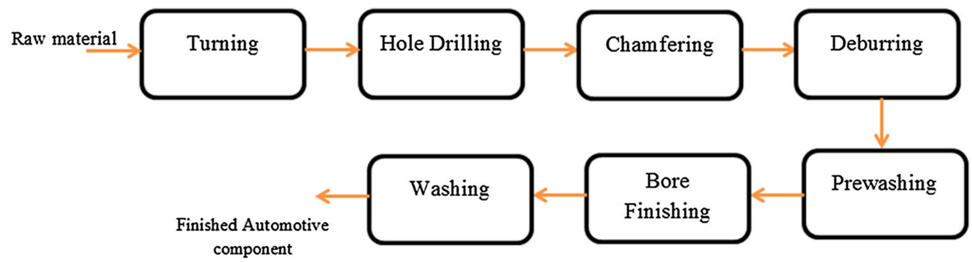


**Fig. 1** Processes involved in manufacturing the automotive component

significance of potential environmental impacts based on the LCI flow results. Interpretation phase identifies, quantifies, and evaluates the results obtained from LCIA. An attempt was made to assess life cycle impact of a manufacturing line using SimaPro 8.1 LCA package. Using SimaPro package the environmental impacts pertaining to the factors of carbon footprint, water eutrophication, air acidification, and total energy consumption are evaluated for each individual process as well as for entire manufacturing line. Carbon footprint usually represents the amount of $CO_2$ and other greenhouse gases, emitted over the life cycle of a process or product (Wiedmann and Minx 2008). Water eutrophication represents the total volume of direct and indirect fresh water used, consumed, and/or polluted (Hoekstra and Chapagain 2011). Air acidification refers to the emission of gases that are released to the atmosphere due to the reaction of acid components of the emissions taken up by atmospheric precipitation (Santoyo-Castelazo et al. 2011). The total energy consumed refers to the sum of all renewable and non-renewable energy required to manufacture the product and to operate the firm (World Wide Fund for Nature, WWF 2002). Manufacturing firms must identify possible steps to reduce the net energy consumed and must utilize non-renewable energy efficiently. These impacts for each process are represented in boxes below the power consumption line in the Sus-VSM.

## Case study

The Sus-VSM methodology is validated by conducting a study where the proposed approach is being applied. The study has been conducted in an automotive component manufacturing organization located in Tamil Nadu, State of India. The firm manufactures around 6000 automotive components/month. The automotive component taken for consideration is used for transmitting power in automotive transmission system. The manufacturing line manufactures only the selected automotive component and has all dedicated resources needed for its manufacture. The machines are scheduled and sequenced and operators are committed to predefined tasks with proper process plans and manufacturing processes. As per the design specifications, turning, drilling, and chamfering operations are performed on the cast iron raw material. Further operations include deburring, prewashing, bore finishing, and washing. The working environment consists of two CNC-turning centers for performing turning and drilling operations, a chamfering machine, two washing machines, and a deburring tool. A total of four operators work in the manufacturing line. The tasks to be performed in the line are broken between the operators in order to reduce idleness and achieve operator work balance. The turning and hole drilling operations are performed by the same operator. Chamfering is exclusively performed by an individual operator, while deburring and prewashing operations are performed by another operator. Finally bore finishing and washing process are performed by an individual operator. The processes involved in manufacturing the automotive component are shown in Fig. 1.

Data such as individual process cycle times, in-process inventory, lead time, value-added cost, non-value-added cost, raw material consumption, water usage, oil usage, coolant usage, worker movement, and potential risks have to be recorded for the construction of Sus-VSM. The data collection and interpretation part for each metric are discussed in the following subsections.

### Computation of process ratio

The time study was performed to collect the individual cycle times of each process. Individual cycle time for each process is shown in Fig. 2. Uptime was calculated for each process based on its individual change over time. Later the details such as takt time and value adding ratio were computed using the formulas 1 and 2.

The firm works 8 h/day with a 20 min lunch break and 5 min tea break and produces 220 components/day. The total cycle time of the product was found to be 15 min and 16 s and process lead time was found to be 0.79 days, i.e., 1137 min. Based on these collected data, takt time and VA ratio were computed. The time line used in the Sus-VSM is shown in Fig. 3.

$$\text{Takt time} = \text{net available time/daily demand} = 2.06\ \text{min}, \quad (1)$$

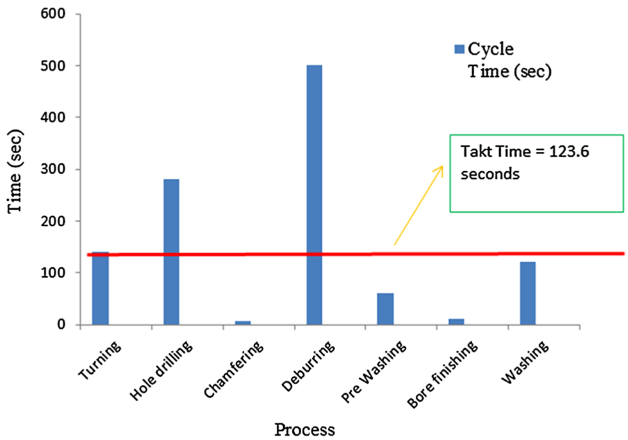


**Fig. 2** Cycle time for each process

$$\text{Process ratio} = (\text{total cycle time/process lead time}) \times 100\,\% = 1.33\,\%. \quad (2)$$

## Computation of VA and NVA costs

Computation of VA and NVA costs helps in satisfying the economic metric of the Sus-VSM. The model suggested by Abuthakeer et al. (2010) is followed for computing VA and NVA costs. VA costs are computed considering the raw material cost, machining cost, and labor costs. NVA costs are computed based on inventory data and holding cost. A cost line is added below the time line in VSM. The value added cost is calculated by the summation of direct cost involved in each process and non-value-added cost is found as the product of WIP and holding cost. The cost data, including manufacturing cost/h, labor cost/h, capital cost/h are introduced.

$$\text{Customer willingness to pay} = \sum_{i=1}^{n} \frac{m_i}{D} + \frac{\text{CT}_i(M_i + L_i)}{3600}. \quad (3)$$

Here $m_i$ denotes material cost for process, $\text{CT}_i$ denotes cycle time for the process, $M_i$ and $L_i$ denote machining cost and labor cost for the process.

$$\text{Customer non willingness to pay} = \sum_{i=1}^{n+1} h_i * \text{WIP}_i. \quad (4)$$

Here $h_i$ denotes holding cost and $\text{WIP}_i$ denotes the work in-process inventory in between the processes.

The cost that the customer is willing to pay also described as value-adding cost for turning operation is calculated using the formula.

$$\begin{aligned}\text{Customer willingness to pay} &= (35,000/180) \\ &\quad + 18((60+40)/3600) \\ &= 195.14 \ \text{INR}.\end{aligned}$$

Similarly, the cost that the customer is not willing to pay also described as non-value adding cost for turning operation is calculated using the formula 4

$$\begin{aligned}\text{Customer non willingness to pay} &= 2160 \times 0.9 \\ &= 1944 \ \text{INR}.\end{aligned}$$

Similarly, total value-adding cost and non-value-adding cost are calculated and the results are included in cost line. In future state map, similar calculations are performed for all operations. The cost line used in Sus-VSM is shown in Fig. 4.

## Raw material consumption

The raw material used for manufacturing the automotive component is cast iron. The consumption of raw material at each process is found by the weight of component before and after machining. The weight was measured using a calibrated electronic weighing machine. The difference in weight of the component before and after machining gives the material loss at each and every stage. The weights are represented in kilograms (kg).The total raw material consumption for manufacturing line is shown in Fig. 5.

## Power consumption

The energy consumption in the line refers to power consumed by the machines to perform the operation and amount of energy spent on transportation of in-process inventory between manufacturing lines. Power consumption is measured by electricity consumed by the machines

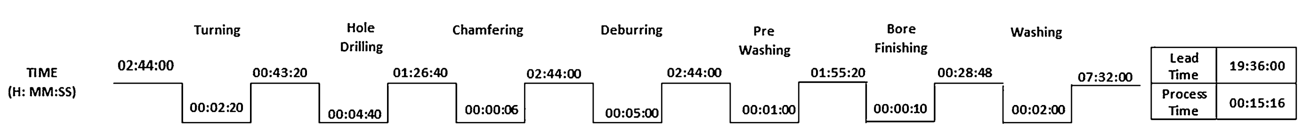


**Fig. 3** Time line used in sustainable VSM

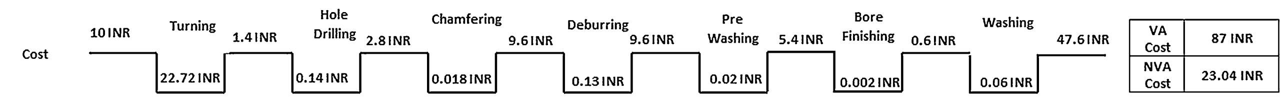


**Fig. 4** Cost line used in sustainable VSM

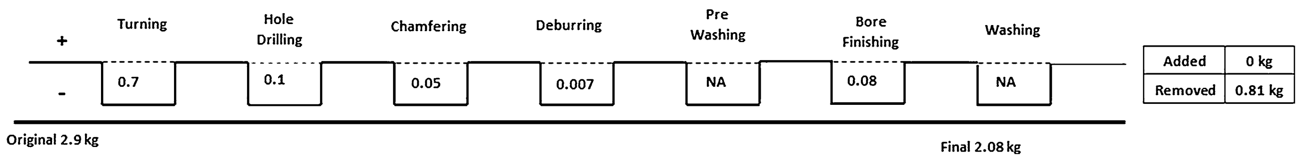


**Fig. 5** Raw material consumption line used in sustainable VSM

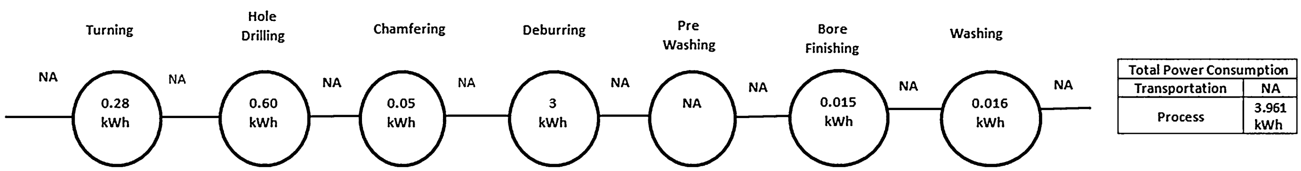


**Fig. 6** Power consumption line used in sustainable VSM

to perform a particular operation on the product. The power consumption in Sus-VSM is measured in kWh. An electricity usage monitor was employed to measure the power consumed by the machines. The power consumption of the component manufacturing line is shown in Fig. 6.

### Process water consumption

In Sus-VSM, amount of process water consumption must be recorded to measure the amount of required water and used water. The net amount represents water not reused by another process in the line or recycled within the plant and essentially lost to the surrounding waterways or municipal waste-water treatment plant (WWTP). If a given process line has an internal WWTP and recycles the water within the plant or from one process to another, this water will not be included in net water metric on the Sus-VSM. In manufacturing line, two processes namely prewashing and washing consume water. Their consumption is measured by amount of water supplied to the machine and amount of water collected after the process. They are measured in liters (l). Prewashing consumes around 10 l of water/day and washing consumes 282 l of water/day. The washing process has an internal WWTP and recycles the water within the plant. So water consumed for washing process is not taken into consideration and hence not represented in Sus-VSM. The visual representation of process water consumption is shown in Fig. 7.

| Required | Used | Net |
|---|---|---|
| 10 litres | 10 litres | 10 litres |

**Fig. 7** Visual representation of process water consumption

### Oil and coolant consumption

The amount of oil and coolant used in manufacturing line is measured in a similar way as that of water consumption. The machines used for performing deburring, prewashing, and bore finishing operations consume oil and machines used for performing turning, drilling, and washing operations consume coolant. The usage of oil and coolant was properly monitored based on delivered quantity and consumed quantity and is frequently maintained in regular intervals. The net usage of oil and coolant for different processes is shown in Table 2.

### Computation of noise level

Noise level prevailing in the workplace must be recorded in Sus-VSM to ensure that employees work in a safe and

Table 2 Oil and coolant consumption details

| S. nos. | Process | Oil consumption (l/day) | Coolant consumption (l/day) |
|---|---|---|---|
| 1 | Turning | NA | 80 |
| 2 | Hole drilling | NA | 100 |
| 3 | Chamfering | NA | NA |
| 4 | Deburring | 1 | NA |
| 5 | Prewashing | 5 | NA |
| 6 | Bore finishing | 0.5 | NA |
| 7 | Washing | NA | 3 |

healthy environment. Noise level exceeding 80 dB puts the operator at risk (OSHA 2008) and duration of exposure to noise also has a significant effect on operator's health. To capture the noise level in a manufacturing environment, formulae 5 and 6 adopted from Faulkner and Badurdeen (2014) are followed for calculating noise dose ($D$) and time weighted average (TWA).

$$D = \frac{\text{time actually spent at sound level}}{\text{maximum permissible time at sound level}} \times 100\,\%, \tag{5}$$

$$\text{TWA} = 16.61\ \log_{10}\frac{D}{100} + 90. \tag{6}$$

TWA calculation for turning process is shown below,

Noise produced by CNC turning center = 75 dB.

For noise level less than 85 dB, the maximum permissible time at sound level is 8 h.

$$D = \frac{455}{480} \times 100\,\% = 94.79,$$

$$\text{TWA} = 16.61\ \log_{10}\frac{94.79}{100} + 90 = 89.614\ \text{ppm}.$$

## Computation of PLI

The ergonomic assessment of employees in the working environment is measured in terms of physical load index (PLI). The approach for evaluating the physical work metric is adapted from Hollmann et al. (1999) where the computation of PLI is discussed. PLI computation uses questionnaire responses which consider the frequency of occurrence (from never to very often) for different body positions and handling of various loads (Faulkner and Badurdeen 2014). Using the standard check sheet, necessary inputs such as employee work posture and movements are recorded using ratings. The obtained ratings are substituted in formula 7 to obtain PLI score. PLI is calculated for each and every process and their scores are included in the process cell box of Sus-VSM. Using the proposed equation, the generated PLI varied from 2.3 to 16.47 for the different operations. The calculation of PLI is shown as

$$\begin{aligned}\text{PLI} = {} & 0.974 \times T_2\text{score} + 1.104 \times T_3\text{score} + 0.068 \\ & \times T_4\text{score} + 0.173 \times T_5\text{score} + 0.157 \\ & \times A_2\text{score} + 0.314 \times A_3\text{score} + 0.405 \times L_3\text{score} \\ & + 0.152 \times L_4\text{score} + 0.152 \times L_5\text{score} \\ & + 0.549 \times \text{Wu}_1\text{score} + 1.098 \times \text{Wu}_2\text{score} + 1.647 \\ & \times \text{Wu}_3\text{score} + 1.777 \times \text{Wi}_1\text{score} + 2.416 \\ & \times \text{Wi}_2\text{score} + 3.056 \times \text{Wi}_3\text{score}.\end{aligned} \tag{7}$$

Based on the work posture as per checklist, ratings were collected for all operations. The PLI score for turning operation was computed and was found as 2.3. Similarly, PLI scores for all other operations were computed and entered in the process cell box of each operation.

## Computation of potential risks in the working environment

Work environment metric helps in assessing the potential risks that exist in a working environment. This metric includes four risk categories where the risk is caused due to electrical systems (E), hazardous chemicals/materials used (H), pressurized systems (P), and high-speed components (S). A rating system varying from 1 to 5 is assigned to each risk associated with the process. For example, in a process if the risks due to hazardous chemicals and materials used are high, a rating of '4' or '5' is assigned to that particular process and it means that 'Risk exist, but has either medium impact and high probability of occurrence or high impact and medium probability of occurrence' or 'Risk is present but has high impact and high probability of occurrence.' Similarly, if the metric is rated as '1' it means that 'Risk is present but has low impact and probability of occurrence.' The risks due to electrical systems (E), hazardous chemicals/materials used (H), pressurized systems (P), and high-speed components (S) that prevail in the manufacturing environment must be captured to ensure employee safety. In automobile component manufacturing line, the potential risks due to four factors are rated and represented in the Sus-VSM. The process of capturing work environment metric for turning operation is shown in Fig. 8.

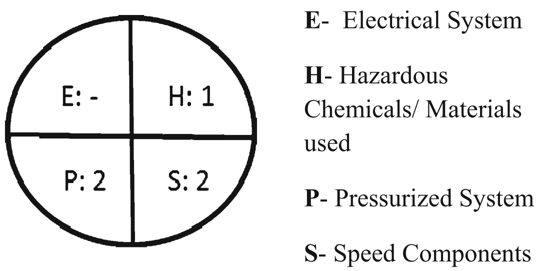


**Fig. 8** Work environment metric for turning operation

## Results and discussions

The results are discussed in the following subsections.

### Analysis of current state sustainable VSM

Based on the computation of Sus-VSM metrics discussed in previous section, value adding ratio of the manufactured line was found to be 1.33 %. VA and NVA costs of individual processes were computed and total VA and NVA costs for each product was found to be 23 and 87 INR. The raw material consumption for all processes was found and overall material lost was observed as 27.93 %. The net power consumed by the automotive component manufacturing line is 3.961 kWh. The total water consumption was observed as 292 l/day in which 282 l were recycled. The computed PLI score for the total line was observed to be 38.87. The current state map for automotive component manufacturing line is shown in Fig. 9.

### Improvements and future state sustainable VSM

After analyzing the current state map, potential improvement actions were planned for each perspective. This section discusses the improvement actions that were planned and implemented to improve the current state.

*Improvements in economic perspective*

The total cycle time for manufacturing the automotive component was found to be 15 min 16 s. The process lead time was 0.79 days (1137.6 min). The takt time was calculated and was found to be 2 min 6 s. VA analysis was performed to find out the bottleneck stations. Based on VA analysis, the hole drilling and deburring processes were observed as bottleneck stations and improvement actions were planned. Standard operating procedure was created for deburring process and 5S activities were being carried out for turning and hole drilling processes. Operator workload balancing was performed for the whole line and equal amount of work was allocated to each operator to avoid idleness and work overload. Apart from these actions, minor Kaizen activities were also performed and

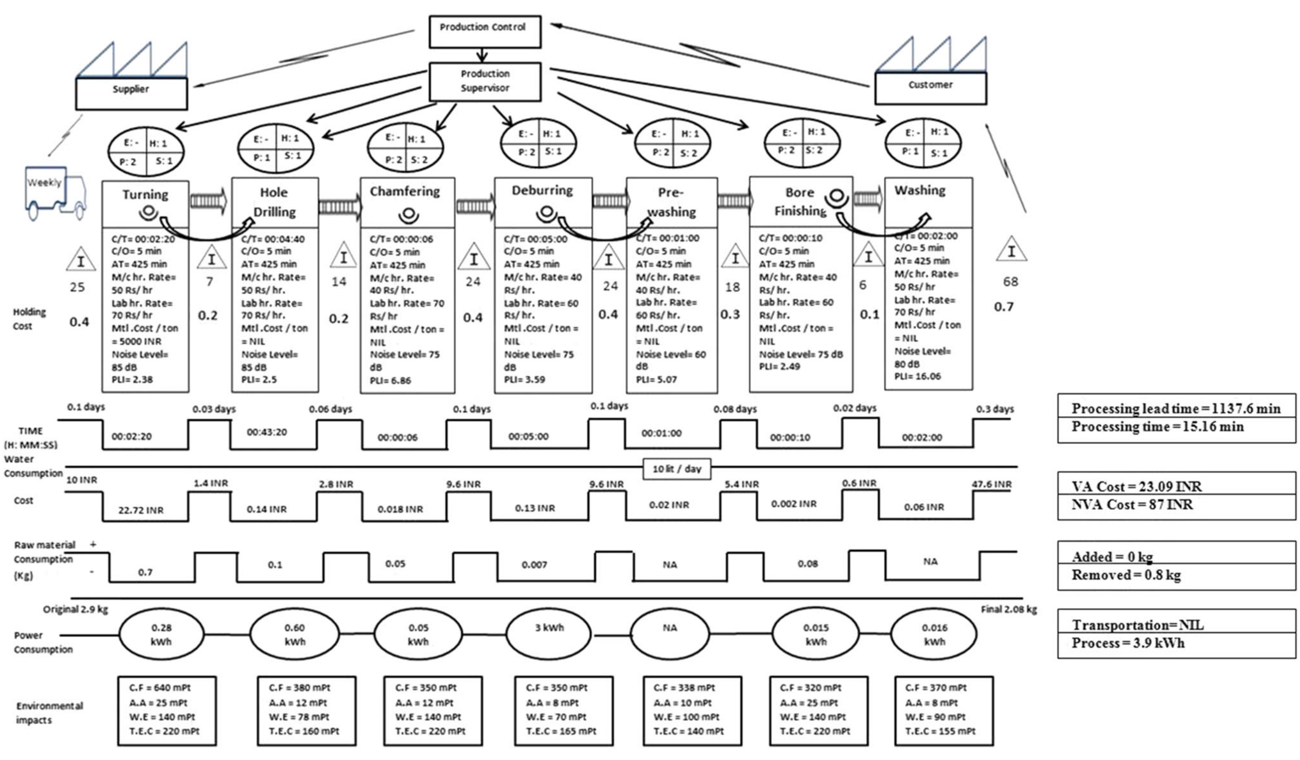


**Fig. 9** Current state map of automotive component manufacturing line

improvements were observed. All these actions lead to reduction in individual cycle time and in-process inventory.

As a reduction in $WIP_i$ was observed after implementation, non-value-adding costs were also reduced. Value-adding costs also reduced reasonably as reduction in cycle time was achieved. Steps were also taken to reduce raw material consumption by providing appropriate orientation and dimensioning to raw material so as to avoid material loss.

*Improvements in environment perspective*

Various tests and experiments were conducted on turning, milling, and deburring machine tools to reduce power consumption by optimizing the aspects of feed rate, spindle speed, and commissioning the electrical unit. Further energy recovery and storage backup units were installed in machine tools to achieve energy efficiency. The washing machines were made to run on low single phase power (previously run on three phase power unit) which is sufficient to run the processes. All these actions decreased the power consumption. The total power consumption of the manufacturing line was reduced by 3.2 kWh from 3.961 kWh and power saving was observed to be 19.12 %.

Washing processes utilize water for cleaning purposes. The firm has inbuilt WWTP and recycles water within the plant. The water used for washing process is only being recycled. The prewashing process consumes water that is not being recycled as the quantity used is scarce compared to that of washing process. Though the firm has a WWTP, a considerable amount of water is wasted as splash lost, leaks, and overflows. To control these losses, level-controlled and self-shutting valves were installed. Further, the tank surfaces were lined using a non-sticky material to avoid loss due to evaporation or condensation. The prewashing machine was installed with a closed loop recirculating water system which helped the firm to reuse its processed water for longer cycles. Also, actions were proposed to use auxiliary cleaning techniques using mechanical cleaning methods, usage of steam, etc., to minimize water usage and to preserve water for future use.

*Improvements in societal perspective*

The potential risk in working environment was assessed. Based on assessment, risk prone areas were identified and improvement actions were taken. Operators working on turning and drilling centers were advised to wear personal protective equipment for safety. Personal protective equipment includes safety goggles, ear muffs, and safety boots. Extension cords were replaced with electric droppers to minimize the electrical hazards. The toxicity of the coolants was frequently checked. Staff development and training programs on work environment safety was periodically conducted.

PLI scores are also used to assess societal sustainability. On analyzing PLI scores, the scores were found to be normal in nature and were not critical. The maximum score was observed for washing operation as it included loading and unloading of components into washing machine repetitively. It was also recommended to use a scissor lift operated pallet for loading and unloading components in the washing machine to minimize operator effort. Further roller operated trolley was also provided for workers to transport components within the line.

*Proposed improvements*

Apart from the implemented Kaizens and improvements observed, further improvement actions were also proposed for improving the firm's sustainable performance. It was proposed to consider the usage of fiber reinforced plastic composed recyclable materials as an alternate material to cast iron to reduce the basic iron ore consumption and to minimize its impacts. It was also proposed to follow eco-friendly practices like green purchasing and ecodesign to make their products and processes more sustainable and to build a stable eco-friendly business enterprise.

## Life cycle impact assessment results

LCIA is performed for evaluating the potential environmental impacts of a product system. In this study, environmental impacts of the automobile component manufacturing line are evaluated using SimaPro 8.1 LCA package. Using this package, it is possible to determine the environmental impact of all processes involved in manufacturing line, and damage assessment can be performed. The overall impacts can be viewed as a single score which involves impact on human health, ecosystem quality, and resources. SimaPro package uses normalization and weighting methods to simplify the interpretation of the results.

The software package has four phases namely goal and scope definition, LCI, LCIA, and interpretation. The goal of the study is to obtain LCA-based environmental information to obtain product's environmental impacts. The functional unit chosen for performing the study is the automotive component. The system boundary includes the stages from the raw material extraction to the disposal phase. Initially, the input data such as processes, operations performed, materials used, water, and coolant consumption are provided as inputs to package. Later the method uses normalization/weighting sets from the list of available methods. For this study, Eco indicator 99(I) version 2.8, is selected as it analyzes the impact assessment of each and every process and shows the results in three categories namely damage

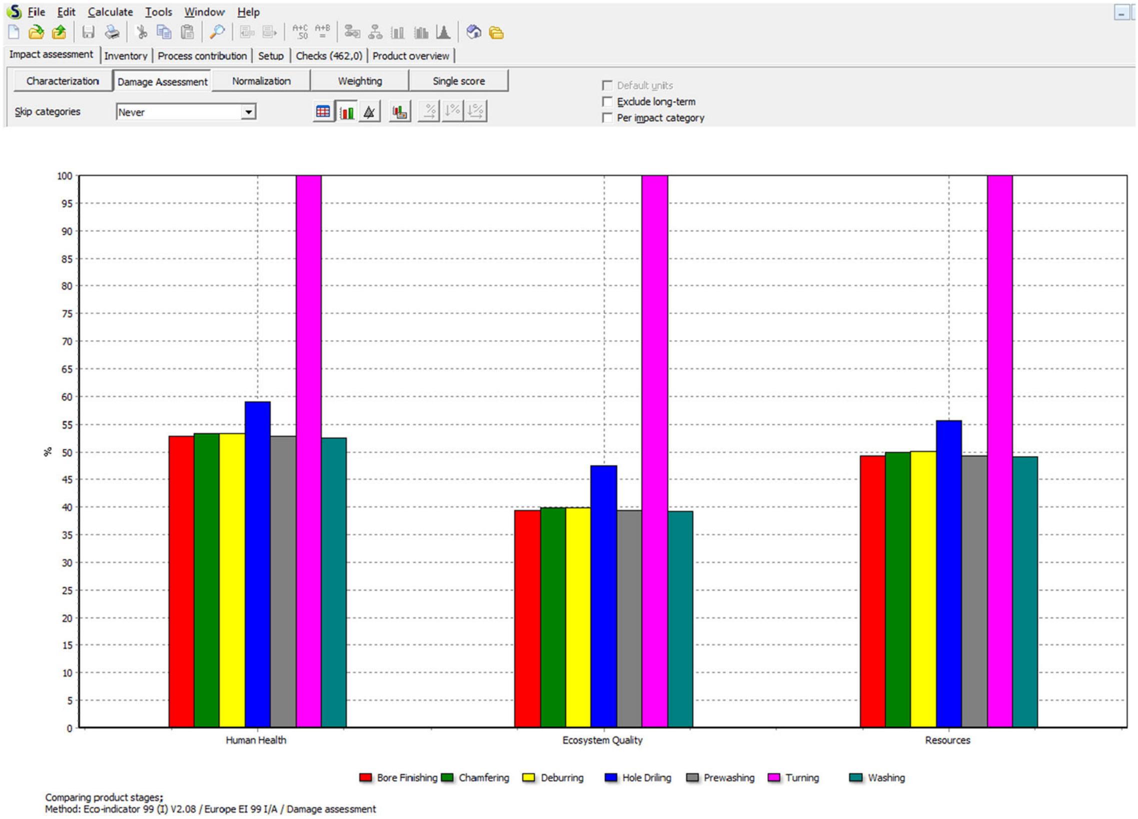


**Fig. 10** Impact assessment pertaining to human health, ecosystem quality, and resources

assessment, normalization, weighting, and single score. The impact assessment of all processes involved in the manufacturing line is calculated on the basis of impact on human health, ecosystem quality, and resources. The necessary details such as machine type, material used for tool and coolant used are given as inputs selected from the parameters library in the software and their effects toward product life and end-of-life are iterated using the software. Based on the results of iteration processes, the impact assessment is performed and impact scores are obtained. The impact results are shown in Fig. 10.

The overall impacts can be viewed as a single score which consists of all impacts for each individual process as shown in Fig. 11.

Based on the results, it is found that the turning operation has the highest impact on all three impact categories followed by hole drilling and deburring processes. In the package, impact scores are represented by milli-point (mPt) which is a unitless number obtained after normalizing the input data. The environmental impacts pertaining to factors namely carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, eco-toxicity, acidification/eutrophication, land use, and minerals are calculated and are categorized into three impact groups namely carbon footprint, water eutrophication, and air acidification. Based on the summarized results, it is found that manufacturing line has the highest impact on human health, followed by resources and ecosystem quality. In the package, total energy consumption is also expressed in mPt as the severity of the impact is calculated after normalizing the values. After normalization, it becomes a unitless number and hence the final output value is expressed in mPt. Table 3 shows the potential environmental impact scores for each process which are computed using the package.

On analyzing the scores of impact categories, it is found that the processes are within the permissible impact limits and impacts can be further reduced on improving the input parameters. After implementing the proposed actions, impacts were again computed and a considerable reduction in all impact categories was observed.

## Selecting the appropriate disposal scenario

Disposal scenario specifies how products are distributed over different end-of-life options, such as disassemblies, reuse, and waste scenarios. A proper disposal scenario that has minimal impacts must be selected for a product to create a state of stability with respect to the eco system, human health, and resources. Using SimaPro 8.0 LCA package, it is possible to select a suitable disposal scenario

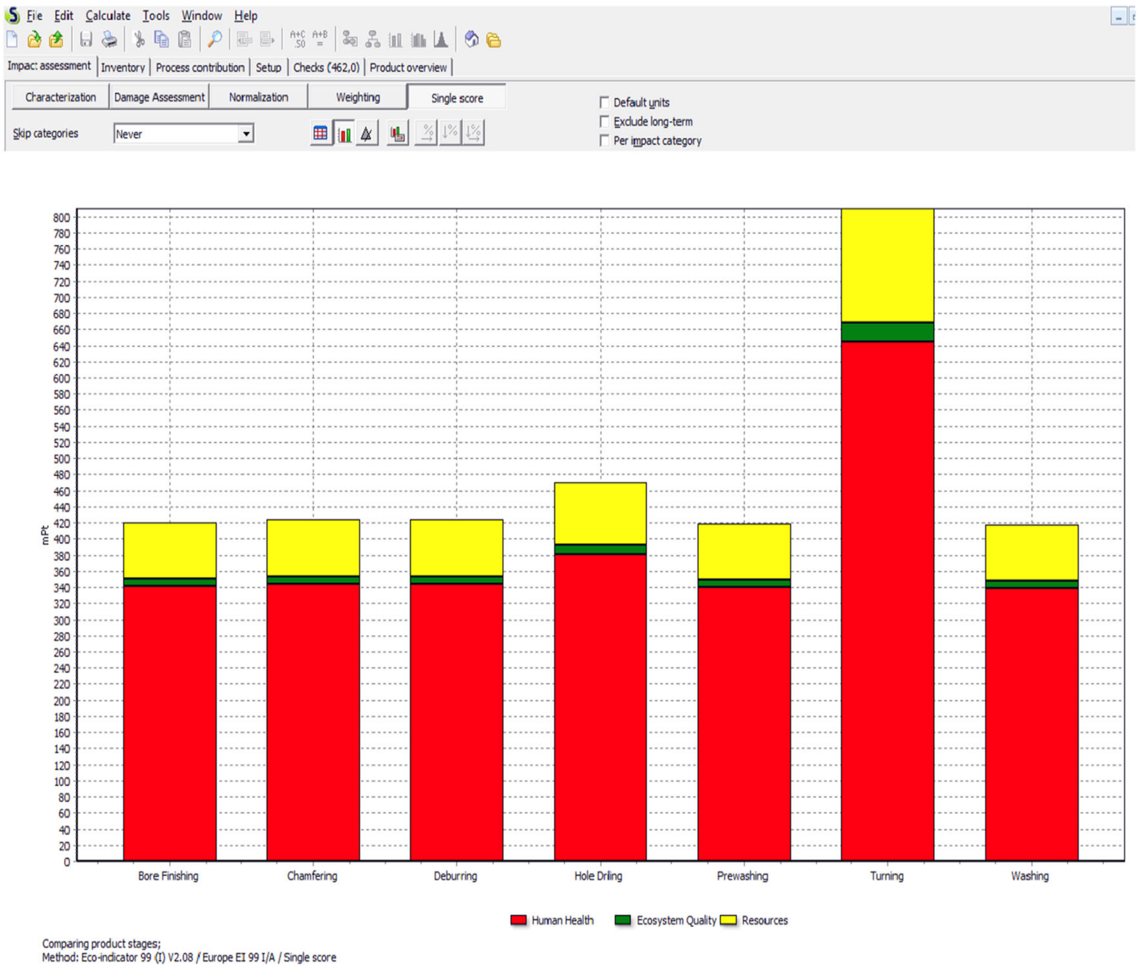


**Fig. 11** Overall impacts for all manufacturing processes

**Table 3** Comparison of environmental impacts

| Impact categories | Current state (mPt) | Future state (mPt) |
|---|---|---|
| Water eutrophication | 758 | 655 |
| Carbon footprint | 2748 | 2570 |
| Air acidification | 89 | 84 |
| Total energy consumption | 1280 | 1140 |

for a particular product. The impacts pertaining to human health, ecosystem quality, and resources for the disposal method can be obtained using the package and disposal method that has minimal impact must be selected.

The selected automotive component is being disassembled after its use phase. The components that can be recycled are being collected and sent for recycling. About 25 % of the component is being recycled. Rest of the components are being collected as scrap and has to be disposed. The manufacturing firm does not follow any particular disposal method and used to dump the scraps in a garbage room. Two disposal scenarios namely landfill and incineration are being compared using the software. Initially, the final product, i.e., the selected automotive component is given as the input product. Landfill and incineration are selected as the disposal scenarios. The damage assessment impact of both disposal methods pertaining to human health, ecosystem quality, and resources are calculated and compared as shown in Fig. 12.

Finally, the impacts of the disposal methods are obtained as a single score comprising the impacts on human health, ecosystem quality, and resources and are expressed in mPt as shown in Fig. 13.

On analyzing the obtained results, it is evident that landfill is the best disposal method as the single score was found to be 24 mPt for incineration and 18.8 mPt for landfill, which means lesser the value, lower the impacts. It is inferred that for a cast iron component, landfill is the best disposal method and has less impact on human health, ecosystem quality, and resources when compared to incineration process where the component is being burnt and creates environmental issues. In landfill method, scrap

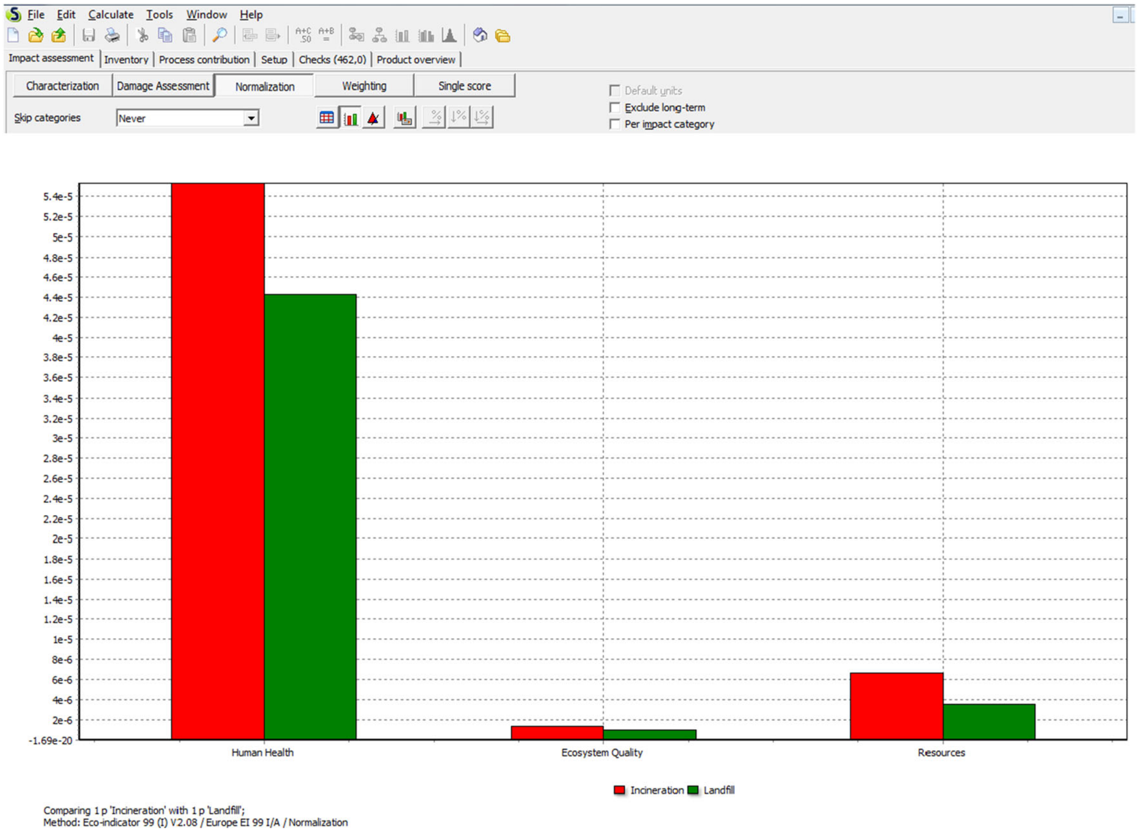


**Fig. 12** Comparison of damage assessment impacts for landfill and incineration methods

is layered in thin spreads and then compacted with a layer of clean earth covering the scrap material and more layers are added over time. This analysis helped the firm in deciding the effective disposal scenario and helped them to reduce the impacts caused by their products during the disposal phase.

### Comparison of results of current state and future state sustainable VSM

Based on the findings from current state Sus-VSM, improvement areas were identified and necessary actions were taken to improvise them. After successful implementation of improvement actions, future state map was derived as shown in Fig. 14.

The percentage improvements pertaining to each metric are computed and are shown in Table 4. Based on the observed improvements, it is proved that the proposed Sus-VSM helped the firm to monitor and analyze the conventional and sustainable metrics and serves as a potential assessment tool to assess the impacts.

A comparative analysis of prior research studies on sustainable manufacturing is shown in Table 5.

## Conclusions

Sustainable manufacturing is concerned with making the process sustainable to develop eco-friendly products with TBL benefits. Lean techniques have potential to ensure greener practices. VSM framework has been used from sustainability focus with TBL metrics. LCA has been used to identify the environmental impacts and such impacts were integrated into VSM framework to provide a visualization of sustainable manufacturing performance. Performing LCA study reflects the quality of the manufacturing process pertaining to the environment. This framework provides leveraged benefits satisfying both lean and sustainable needs. A case study conducted in an Indian automotive component manufacturing organization has been demonstrated. The study helped in enhancing the firm's sustainable performance and also helped in reducing its environmental impacts. One of the future research directions mentioned by Faulkner and Badurdeen (2014) to visually represent desired future state of performance has been fulfilled in the present study. The developed framework provides insight into the organizations with a comprehensive assessment of energy consumption and value added by the process. This new

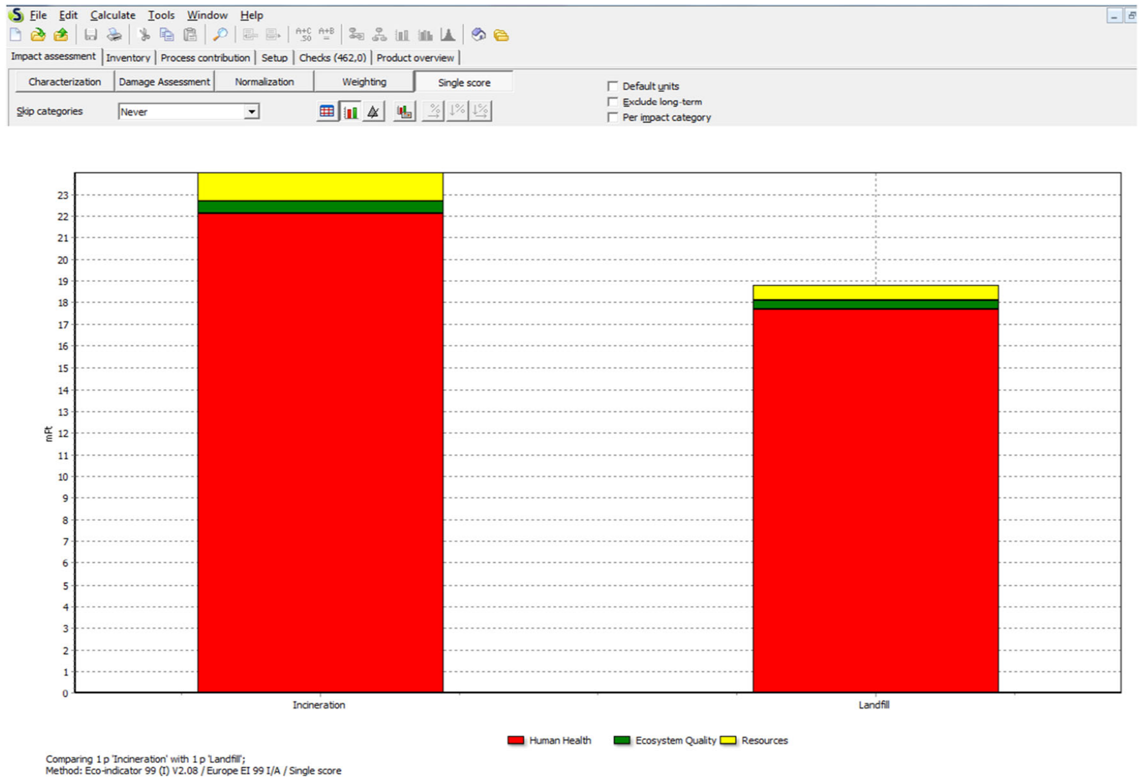


**Fig. 13** Comparison of impacts as a single score for landfill and incineration methods

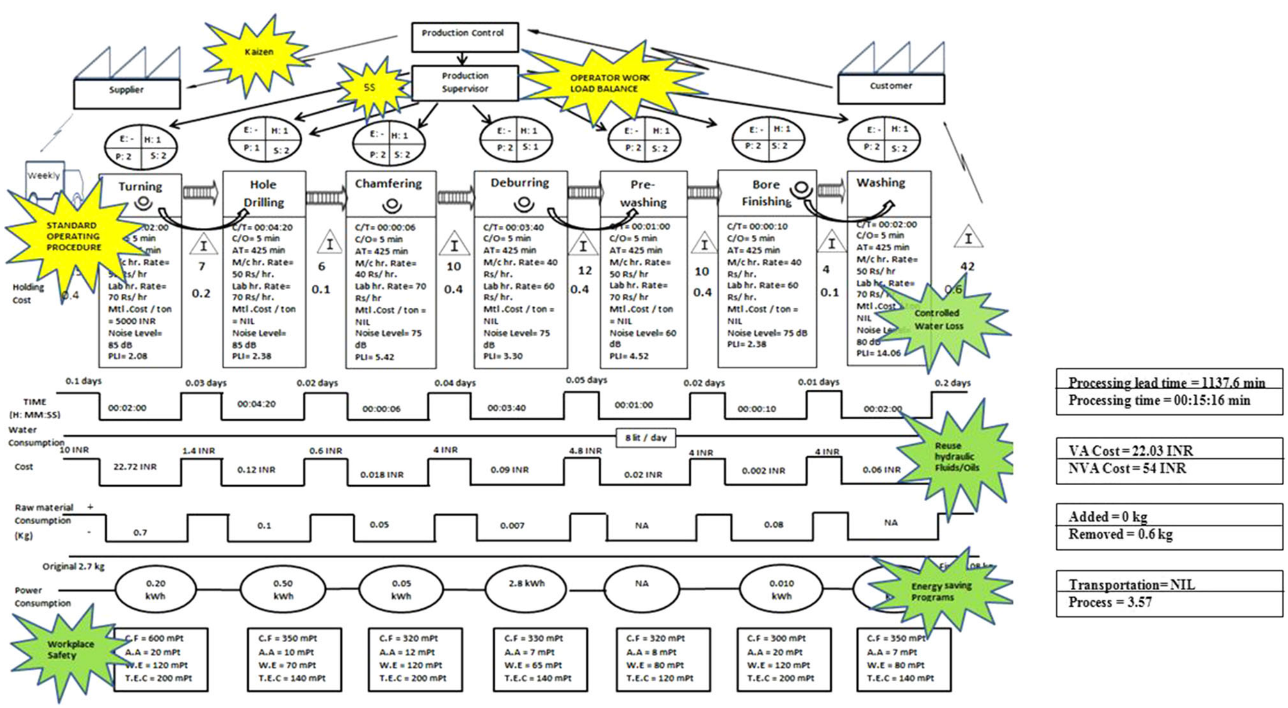


**Fig. 14** Future state map of automotive component manufacturing line

**Table 4** Comparison of results

| Driver | Process parameters | Current state map | Future state map | Percentage improvement (%) |
|---|---|---|---|---|
| Economy | Cycle time | 15 min 16 s | 14 min 38 s | 6 |
| | Lead time | 1137 min | 547 min | 52 |
| | Process ratio | 1.33 | 2.62 | 51 |
| | Value-adding cost | 23.09 INR | 22.03 INR | 5 |
| | Non-value-adding cost | 87 INR | 54 INR | 38 |
| | Raw material consumption | 0.8 kg | 0.6 kg | 25 |
| | Power consumption | 3.961 kWh | 3.2 kWh | 19.12 |
| Environment | Water consumption | 758 | 655 | 14 |
| | Carbon footprint | 2748 | 2570 | 7 |
| | Air acidification | 89 | 84 | 6 |
| | Total energy consumption | 1280 | 1140 | 11 |
| Society | PLI | 38.87 | 32.14 | 18 |

**Table 5** Comparative analysis of prior research studies

| Authors | Tools | Objectives | Environmental metrics | Economical metrics | Societal metrics |
|---|---|---|---|---|---|
| Simons and Mason (2002) | Sustainable VSM (SVSM) | Created a sustainable value steam map to evaluate the environmental metrics | ✔ | – | – |
| US EPA (2007a) | EPA lean and environmental toolkit | Created a toolkit to evaluate the lean and environmental performance of manufacturing firms | ✔ | – | – |
| US EPA (2007b) | EPA lean and energy toolkit | Modified the EPA lean and environmental toolkit with energy metrics | ✔ | – | – |
| Torres and Gati (2009) | Environmental VSM (EVSM) | Extended the EPA lean and environmental toolkit and created an environmental VSM (EVSM) which emphasize on water consumption | ✔ | – | – |
| Fearne and Norton (2009) | Sustainable value chain map (SVCM) | Created a sustainable value chain map (SVCM) with sustainability metrics | ✔ | – | – |
| Paju et al. (2010) | Sustainable manufacturing mapping (SMM) | Created a new methodology named sustainable manufacturing mapping (SMM) which combines discrete event simulation (DES) and LCA with conventional VSM | ✔ | – | – |
| Kuriger and Chen (2010) | Energy and environment VSM (EE-VSM) | Created a VSM which focused on evaluating the energy and environmental performance of manufacturing firms | ✔ | – | – |
| Kuriger et al. (2011) | Lean sustainable production assessment tool | Proposed a lean sustainable production assessment tool | ✔ | – | – |
| Dadashzadeh and Wharton (2012) | Green VSM | Created a VSM which focused only on evaluating environmental performance | ✔ | – | – |
| Faulkner and Badurdeen (2014) | Sustainable value stream mapping (Sus-VSM) | Created a sustainable value stream mapping (Sus-VSM) to evaluate the sustainable performance of manufacturing firms | ✔ | – | ✔ |
| Proposed | LCA integrated sustainable manufacturing mapping | Created a VSM integrated with life-cycle assessment (LCA) for ensuring sustainable manufacturing | ✔ | ✔ | ✔ |

framework which integrates LCA and VSM ensures to improve sustainable performance and thus contributes the scientific value. It also helps the practitioners to identify specific improvement opportunities for reducing the environmental impacts along with conventional lean and sustainable initiatives. The applicability of this framework is limited to manufacturing firms and process industries, as they contribute more toward the environmental impacts.

The developed framework need to be tested in varied manufacturing streams to improve the practical validity. More relevant studies can be performed to test its generic applications and limitations. Parallel iterations with existing LCA methods can be performed to test its accuracy. Further, lack of expertise, facilities, and eco-awareness may be considered as the barriers which stop a firm from not evaluating its environmental impacts. In future, a dedicated expert system could be developed for automating the analysis.

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## Appendix

See Table 6.

**Table 6** Questionnaire for calculation of physical load index (PLI) of turning operation

| | **Trunk** | **Never** | **Seldom** | **Sometimes** | **Often** | **Very often** |
|---|---|---|---|---|---|---|
| $T_1$ | Straight, upright | | | | | * |
| $T_2$ | Slightly inclined | | * | | | |
| $T_3$ | Strongly inclined | * | | | | |
| $T_4$ | Twisted | * | | | | |
| $T_5$ | Laterally bent | * | | | | |
| | **Arms** | **Never** | **Seldom** | **Sometimes** | **Often** | **Very often** |
| $A_1$ | Both below shoulder | | | | * | |
| $A_2$ | One arm above shoulder | * | | | | |
| $A_3$ | Both arms above shoulder | * | | | | |
| | **Legs** | **Never** | **Seldom** | **Sometimes** | **Often** | **Very often** |
| $L_1$ | Sitting | * | | | | |
| $L_2$ | Standing | | | | | * |
| $L_3$ | Squatting | * | | | | |
| $L_4$ | Kneeling with one or both | * | | | | |
| $L_5$ | Walking, moving | | | * | | |
| | **Weight-upright** | **Never** | **Seldom** | **Sometimes** | **Often** | **Very often** |
| $Wu_1$ | Light | | | * | | |
| $Wu_2$ | Medium | * | | | | |
| $Wu_3$ | Heavy | * | | | | |
| | **Weight-inclined** | | | | | |
| $Wi_1$ | Light | * | | | | |
| $Wi_2$ | Medium | * | | | | |
| $Wi_3$ | Heavy | * | | | | |
| | | **Never** | **Seldom** | **Sometimes** | **Often** | **Very often** |
| Scores assignable | | **0** | **1** | **2** | **3** | **4** |

Based on Hollmann et al. (1999)

$$\text{PLI} = 0.974 \times 1 + 1.104 \times 0 + 0.068 \times 0 + 0.173 \times 0 + 0.157 \times 0 + 0.314 \times 0 + 0.405 \times 0 + 0.152 \times 0 + 0.152 \times 2 + 0.549 \times 2 + 1.098 \times 0 + 1.647 \times 0 + 1.777 \times 0 + 2.416 \times 0 + 3.056 \times 0$$

$$\text{PLI} = 2.376$$

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