Achieving Lean and Improving Sustainability through Value Stream Mapping for Complex Manufacturing

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Abstract

Lean manufacturing has helped companies to achieve reduced lean wastage, productivity, quality, and resource optimization. Value stream mapping (VSM) is an important tool in achieving lean orientation. It helps companies in enhancing the competitiveness of their production systems. Although, VSM is a very useful tool to achieve lean orientation, it suffers from several drawbacks. It is static pencil-and-paper tool. It cannot handle complex value streams. It does take into account monetary measures e.g. profitability of the value stream. Also, it does not include environmental impact of the value stream. This research paper overcomes the drawbacks of the VSM tool through an innovative framework involving the usage of discrete event simulation, box score, and life cycle assessment (lca).

1. Introduction

The manufacturing companies are today facing tremendous global competition. Lean manufacturing helps companies in enhancing their competitiveness by reducing costs and waste minimization.1 The activities that are wasteful in a production system have to be minimized systematically.2 There are many tools to achieve lean orientation e.g. standardized work, poka-yoke, 5S, VSM. VSM is an important tool to achieve lean orientation. VSM, however, suffers from several limitations:

- VSM is a static tool. It provides only a static snapshot of the production system.
- VSM cannot easily handle complex production scenarios. VSM can easily handle simple single product-based manufacturing situations. However, complex production scenarios involving multi-level bills of materials (BOM), or multi-product product situations cannot be easily handled.
- VSM does not take into account monetary measures within the value stream e.g. costs, profitability etc.
- VSM does not take into account environmental impact associated with the value stream.

This research paper overcomes the limitations of the VSM through some of the following counter-measures (Refer to the table 1):

| Limitation of the VSM | Counter-measure employed in this research paper |
|-----------------------|-------------------------------------------------|
| VSM is a static tool.  | • VSM is a static tool which only provides a static snapshot of the manufacturing situation. This limitation is overcome through the use of discrete event simulation software Extendsim. |
| VSM cannot easily handle complex production scenarios. | • VSM cannot easily handle complex production scenarios e.g. multi-level BOM, multi-product |

Table 1: Limitations of VSM
manufacturing situations. This limitation is overcome through the use of discrete event simulation software Extendsim.

| Requirements                                      | Conventional VSM | Proposed Approach |
|---------------------------------------------------|-------------------|-------------------|
| Static Approach                                   | ●                 | ●                 |
| Application to complex production streams         | ○                 | ●                 |
| Dynamic Approach                                  | ○                 | ●                 |
| Finding optimal level of resources (man and machine resources) | ○ | ● |
| Insight into financial performance.               | ○                 | ●                 |
| Prioritization of kaizen continuous improvement Initiatives | ○     | ●                 |
| Ability to perform feasibility check              | ○                 | ●                 |
| Achieve global optimization                       | ○                 | ●                 |
| Environmental impact of the value stream          | ○                 | ●                 |

One of major handicaps of the VSM process is that it does not include environmental impact of the value stream. The proposed framework uses a discrete event simulation model, combined with lean box score, and lca. The proposed methodology is demonstrated for a lamp post manufacturer case.

2. Literature review

Lean manufacturing emerged from Toyota Motor Corporation. This philosophy was called Toyota Production System. \(^3,4\) The production system is organized and oriented in such a manner that eight lean wastes (Muda) are minimized. VSM is one of the most important tools for achieving lean orientation. VSM as a tool was introduced for achieving lean orientation. \(^5\) VSM is very powerful tool for achieving lean manufacturing. However, VSM has certain limitations (refer to table 1, and table 2). Researchers have suggested many approaches for overcome these limitations. The approaches include heuristics, discrete event simulation etc. Some of the selected research works have been summarized in the table 3.

Table 3: Literature Survey

| Author(s)                           | Contribution                                                                 |
|-------------------------------------|-----------------------------------------------------------------------------|
| Khaswala and Irani \(^6\)           | Suggested Value network mapping (VNM) approach for complex flows.            |
| Braglia, Carmignani, and Zammori \(^7\) | Suggested Improved VSM approach (IVSM) approach for Complex production streams. |
Author(s) | Contribution
--- | ---
McDonald et al. | Using Discrete event simulation (DES) for lean for Engineering-to-order (ETO) products.
Lian and Landeghem | Proposed DES for lean.
Abdulmalek and Rajgopal | Proposed VSM combined simulation (for steel mill – process industry))
Seth et al. | Proposed, simplifications, and approximation in VSM.
Alperen Bal, Cemil Ceylan & Caner Taçoğlu | Combined VSM with DES for a emergency unit.
Braglia, Froisolini, Zammori | Suggested fuzzy algebra with VSM
Parthanadee and Buddhakulsomsiri | Demonstrated achieving lean through DES.
Samant, Mittal and Prakash | For a chassis production system, suggested the use of VSM combined with DES.
Tapping et al | Step by step method for achieving lean using value stream map (VSM).
Faulkner and Badurdeen | Proposed metrics for environmental performance.
Vinodh et. al. | Suggested methodology for sustainable value stream mapping.
Torres and Gati | Proposed a managerial tool Environmental VSM (EVSM) to address environmental and economic aspects of a production system.
Paju et. al. | Proposed an assessment based on VSM. The framework includes VSM, DES, LCA etc.

Research Gap and Aim of Research:
From table 3, it is clear that achieving green and lean simultaneously through VSM is a research topic that has not been explored completely. There is a room for an alternate framework for achieving lean orientation for the value stream. It is difficult to achieve lean orientation, especially for complex value streams using traditional VSM approach.

3. Methodology
To overcome these limitations of VSM mentioned in section 1, this research paper proposes a framework which integrates LCA with VSM. It also integrates lean box score and environmental metrics into the framework. The main focus of this research is to study the effect of environmental impact of the value stream. This research also helps in our endeavor to have a lean and green production system.

3.1 Case Study
The framework has been explained using a case study. This case study pertains to a manufacturer of lamp post (refer figure 1) This product is currently in design/prototyping stage. The idea here is that it may be prudent to take up lean manufacturing at the design stage, because most of capex decisions are taken early in the design cycle. This is in line with concurrent design principles. Most of the available literature on lean manufacturing studies focusses on cases where full scale production is taking place. This has limited usefulness as all the capex decisions have already been made.
Any organizational improvement effort should begin by jotting down organizational priorities. Organizational Priorities are given below:

- Meet the production target of 2000 pieces per week
- Meet the quality target: First time right 99%
- Timely delivery: meet the on-time-delivery target of 99%
- Minimize Production Cost
- Meet the revenue target: $32,000 per week
- Minimize environmental impact of the value stream.

At this point, the process flow diagram is created detailing the sequential representation of the manufacturing processes used for manufacturing the product. The process flow diagram is shown in figure 2.

![Process Flow Diagram](image)

**Figure 2: Process flow diagram**

The process parameters for the processes shown in the process flow diagram is shown in table 4.

The current process parameters (estimated) during initial stage (current value stream map) are given in table 4.

### Table 4: Process Parameters

| Process Name   | Process Code (refer figure 2) | Cycle Time (minutes) | Set-up Time (min) | Transfer Batch Size (initially assumed value) | No of Machines | No of Operators | Weekly Depreciation Cost (USD) | Operating Cost (per operation) (USD) |
|----------------|--------------------------------|----------------------|-------------------|-----------------------------------------------|----------------|-----------------|----------------------------------|-----------------------------------|
| Welding        | AB                             | NORMAL (2, 0.2)      | 6                 | 5                                             | 9              | 11.5            | 0.068                            |                                   |
| Painting       | AB1                            | NORMAL (30, 4.5)     | 7                 | 5                                             | 7              | 5.8             | 0.036                            |                                   |
| Deburring      | B2                             | NORMAL (10, 1.5)     | 2                 | 5                                             | 6              | 1.9             | 11.5                            | 0                                 |
| Drilling       | A2                             | NORMAL (30, 4.5)     | 4                 | 5                                             | 11             | 40*             | 0.2                             |                                   |
| Blanking       | A1                             | NORMAL (2, 0.2)      | 4                 | 5                                             | 5              | 96.2            | 0.2                             |                                   |
| Tube Shearing  | B1                             | NORMAL (2, 0.2)      | 6                 | 5                                             | 5              | 2.2             | 0.2                             |                                   |

*Shared between operations; Cost of operator $99 (per week); Number of operators 25; Number of trolleys 25
The process parameters will be used for achieving lean orientation. This has been detailed in Annexure – A.

At this time, we must try to carry out life cycle assessment (LCA) of the products constituting the assembly. Life cycle assessment (LCA) is a multi-step process for computing the environmental burden of a product/service. Typically, it includes the following stages:

a) goal and scope
b) inventory analysis
c) impact assessment
d) interpretation.

Goal and Scope: Some of key parameters that are defined during the goal and scope stage are discussed below:

- Functional unit: The functional unit for the LCA is a single product.
- Goal and Scope: Goal: The goal of LCA is to carry out environmental impact assessment of all the products constituting the assembly in all stages of the product life cycle (cradle to grave).
- System boundary: The system boundary includes all the upstream and downstream processes. The system includes the technosphere (economic system). Activities in the technosphere cause undesirable effects in the ecosphere.

Life Cycle Inventory (LCI): The life cycle inventory represents quantified flows (both mass and energy flows) representing unit processes. The flows (mass flows) and the processes used are given in table 5.

Life Cycle Impact Assessment (LCIA): In this step the environmental impact analysis due to LCI is carried out in order to find the Life Cycle Environmental Impact (LCIA). LCIA results are shown in table 6. The tool used here is lcacalculator.com.

### Table 5: Life Cycle Inventory

| Stage                  | Inventory List (for various processes) | Quality | Units |
|------------------------|----------------------------------------|---------|-------|
| Raw Material Extraction|                                        |         |       |
| Plate                  |                                        | 10      | Kg    |
| Tube                   |                                        | 16      | Kg    |
| Transport of Raw Materials |                                   |         |       |
| Transport Freight Lorry (3.5 - 7.5) T(Plate and Tube)( Kg) | 20 | Km |
| Manufacturing          |                                        |         |       |
| Plate                  | Stamping / Laser cutting               |         |       |
|                        | Machining (25%)                        |         |       |
|                        | Welding                                | *       |       |
| Tube                   | Hot Rolling                            |         |       |
|                        | Machining (25%)                        | *       |       |
| Transport of Finished Goods |                                   |         |       |
| Transport Freight Lorry (3.5 - 7.5) T(Assembly Weight Kg) | 150 | Km |
| Disposal               |                                        |         |       |
| Disposal (T9)          | Lamppost Assembly                      |         |       |
(* The software works the quantities for the unit processes internally)

Table 6: Life Cycle Impact Assessment (Global Warming Kg CO₂)

| Stage                      | Inventory List (for various processes)                  | Quality | Units |
|----------------------------|--------------------------------------------------------|---------|-------|
| Raw Material Extraction    | Plate                                                   | 24      | Kg    |
|                            | Tube                                                    | 35      | Kg    |
| Transport of Raw Materials | Transport Freight Lorry (3.5 - 7.5) Tonne (Plate and Tube) (Kg) | 0.25    | Kg    |
| Manufacturing              | Plate                                                   |         |       |
|                            | Stamping / Laser cutting                                | 4.2     | Kg    |
|                            | Machining (25%)                                         | 15      | Kg    |
|                            | Welding                                                 | 0.6     | Kg    |
|                            | Tube                                                    |         |       |
|                            | Hot Rolling                                             | 7.6     | Kg    |
|                            | Machining (25%)                                         | 24      | Kg    |
| Transport of Finished Goods| Transport Freight Lorry (3.5 - 7.5) T (Assembly Weight Kg) | 1.9     | Kg    |
| Disposal                   | Lamppost Assembly                                       | 0.1     | Kg    |

A cumulative assessment of the degree of lean orientation, as well as the environmental impact can to be carried out. This research paper proposes the value stream map in conjunction with lean and green box score (as the accounting framework for this cumulative assessment) for a comprehensive evaluation of the lean orientation, as well as the environmental impact of the value stream. The value stream map is shown in figure 3. This VSM differs from the traditional VSM in a sense that environmental impact trend lines have been added at the bottom of the VSM. The box score provides insights into the value stream from the financial, resource capacity, operational standpoint.

Figure 3: Value stream map
4. Results and Discussions

The lean box score prior to implementation of the kaizens is given in table 7.

Table 7: The lean and green box score

| Lean Box Score | Dock-to-Dock Days | 4.25 days |
|----------------|-------------------|-----------|
| Operational    | First Time Through (FTT) | 90%       |
|                | On Time Delivery/Service Level | 100%      |
| Floor Space    | Productive Utilization | [0.6, 0.6, 0.4, 0.6, 0.1, 0.1] |
|                | Non-productive Utilization | [0.03, 0.04, 0.02, 0.02, 0.04, 0.04] |
|                | Available Utilization | [0.4, 0.0, 0.6, 0.4, 0.9, 0.9] |
| Financial      | Sales per person (USD) | 320       |
|                | Inventory Value    | 412       |
|                | Revenue            | 8000      |
|                | Material Costs     | 5000      |
|                | Conversion Costs (USD) | 3308*     |
|                | Value Stream Profit (USD) | -720     |
|                | Sales per Product (USD) | 16        |
| Environmental  | Climate Change (KgCO2) | 113       |

The evaluation provides key insights into the value stream, and helps in coming up with the kaizen continuous improvement ideas. The following kaizen improvement ideas have been identified: The continuous improvement efforts (kaizens) can be towards achieving lean orientation (lean kaizens), or towards reducing environmental impact (environmental kaizens). The lean and the environmental kaizens have been summarized in table 8.

Table 8: The proposed Kaizen improvement initiatives

| Lean Kaizens | Kaizen No | Description of Kaizen | Implementation |
|--------------|-----------|-----------------------|----------------|
|              | 1         | Reduce Conversion Cost | - Resource Optimization: it can be seen that the conversion cost contributes maximum towards the overall cost. So, the reduction of conversion cost deserves maximum attention. Conversion cost can be reduced through resource optimization. This includes both man and machine resources. Resource optimization can be carried out using the Discrete Event Simulation software. Extendsim (evolutionary optimizer) has been used here. A more detailed discussion of resource optimization has been discussed in Appendix A. |
|              |           | Reduce environmental burden associated | - There is an environmental burden associated with the value stream. The environmental burden associated with the value stream is listed in table 6. The environmental burden has been calculated using online tool (lcacalculator.com (based on Ecoinvent database)). Table 6 gives a comparison of environmental impacts during various stages |
with the value stream of the product life cycle. This environmental impact can be reduced using the following steps:

- From figure 4 it can be seen that raw material extraction is the major contributor to the environmental impact. This can be reduced considerably by increasing the recycled content in the raw materials.
- From figure 5 it can be seen that of all the manufacturing processes, machining process is the next biggest contributor to environmental burden. Machining process adds considerably to the carbon emissions. From figure 5 it can be seen that by reducing machining can reduce carbon emissions considerably. The product designers should try to focus on reducing the machining process as much as possible.

**Figure 4: Breakup of Environmental Impact due various life cycle stages of product**

**Table 9: Lean box score (future state)**

| Lean Box Score | Environmental Impact (Kg CO2) |
|----------------|--------------------------------|
| Raw material extraction | **Stamping** |
| Transport               | **Machining** |
| Manufacturing            | **Welding** |
| Disposal                 | **Hot Rolling** |
Operational

|                  |                  |
|------------------|------------------|
| Dock-to-Dock Days| 5                |
| First Time Through (FTT) | 90%            |
| On Time Delivery/Service Level | 100%          |

Floor Space

|                  |                  |
|------------------|------------------|
| Productive       | [0.9, 0.8, 0.7, 0.9, 0.4, 0.4] |
|                  | [0.04, 0.06, 0.03, 0.02, 0.17, 0.20] |
| Non-productive   | [0.04, 0.06, 0.03, 0.02, 0.17, 0.20] |
| Available        | [0.1, 0.1, 0.3, 0.1, 0.4, 0.4] |

Financial

|                    |                  |
|--------------------|------------------|
| Sales per person (USD) | 320            |
| Inventory Value     | 317              |
| Revenue             | 8000             |
| Material Costs      | 5000             |
| Conversion Costs (USD) | 1631           |
| Value Stream Profit (USD) | 1052          |
| Sales per Product (USD) | 16             |
| Cost Per Product (USD)  | 14              |

Environmental Impact

40% reduction in Kg CO2 emissions can be targeted (approximately)

The proposed methodology is very useful for achieving lean orientation for the complex value stream. It helps to optimize on the relevant parameters of the complex VSM. It helps to focus and prioritize the kaizen improvement ideas. It helps to check feasibility of the future state VSM through the optimization of lean box score. Some of the unique advantages of this innovative approach:

a) Ability to achieve lean orientation for a complex value stream
b) Unique plug and play and approach in modeling the value stream made up of standardized components
c) Ability to prioritize kaizen improvement ideas
d) Ability to perform feasibility checks, i.e., whether a certain kaizen improvement idea is feasible. The parts can be produced with the available resources at the required performance level.

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6. **Annexure - A**

The resource optimization is carried out by Extendsim optimizer. The Extendsim optimizer is an evolutionary optimizer. This optimizer is an integral part of the software Extendsim (discrete event simulation software). The optimizer is based on evolutionary algorithm. It mimics the common biological evolutionary processes such as mutation, recombination and selection.

![Extendsim simulation model (for a single process)](image)

Selected parameters from the optimization model shown in figure 8 are linked to optimizer. The optimizer seeks the desired goal. The optimizer block within Extendsim is presented in Figure 8. Top part of the optimizer window stores the parameters to be optimized. These parameters are derived from simulation model. These parameters are linked to the parameters within the simulation model. The objective function is stored in the bottom part of the window. The simulation model is run multiple times with different values of the parameters. The evolutionary optimizer tries to come up with an optimal solution with favorable values of the lean box score (objective function). Here the lean box score parameter: value stream profit is the objective function. The decision variables are the resource (man and machine) whose optimal values are being sought.

![Extendsim simulation model (for a single process)](image)
in Figure 8. Top part of the optimizer window stores the parameters to be optimized. These parameters are derived from simulation model. These parameters are linked to the parameters within the simulation model. The objective function is stored in the bottom part of the window. The simulation model is run multiple times with different values of the parameters. The evolutionary optimizer tries to come up with an optimal solution with favourable values of the lean box score (objective function). Here the lean box score parameter: value stream profit is the objective function. The decision variables are the resource (man and machine) whose optimal values are being sought.

Figure 8: Extendsim evolutionary optimizer

Optimization model:

\[
\text{Value Stream Profit} = (\sum_i^n (M_i S_i) - (\sum_m^k (H_m R_m) + \sum_o^i (H_o O_o)));
\]

\begin{itemize}
  \item \(M_i\) = Number of pieces of product sold of type \(i\)
  \item \(S_i\) = Price of product \(i\)
  \item \(H_m\) = Number of hours resources a resource of type \(m\) employed
  \item \(R_m\) = Resource rate of type \(m\)
  \item \(H_o\) = Time of operations of type \(o\)
  \item \(O_o\) = Operation cost of type \(o\)
\end{itemize}

After the optimization, we are one step closer to lean orientation. The lean box score are shown in table 9. The resource optimization leads to line balancing as well.