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Lean Carbon Mapping Approach to Optimize Paper Usage in Offset Printing Industries

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Abstract

Paper waste in offset printing industries contributes not only to economic inefficiencies but also to environmental degradation through increased CO_2 emissions. This study explores the integration of Lean Carbon Mapping (LCM) with traditional Lean tools to optimize paper usage and reduce the carbon footprint associated with printing operations. A case-based research design is applied across selected offset printing units in Tamil Nadu, India. The methodology involves Value Stream Mapping (VSM), identification of high carbon-emitting activities, and targeted interventions using Lean practices such as 5S, Kaizen, and Standard Working procedures. The implementation of Lean Carbon Mapping resulted in a 45% reduction in paper waste and a 45% decrease in estimated carbon emissions linked to material handling and print defects. The findings demonstrate the potential of LCM as a strategic tool for advancing both operational efficiency and environmental sustainability in the printing sector.

Keywords
Lean Carbon Mapping (LCM), Offset Printing Industry, Waste Reduction, 5S, Value Stream Mapping (VSM).

1. Introduction
Printing is the stage in the communication process where information becomes visible and tangible to users. The final product should not only effectively convey information but also reflect a sense of high quality suited to its purpose. In fact, much of press optimization focuses on minimizing startup waste and adopting methods that reduce both power and substrate consumption. Offset printing remains a dominant process in commercial print production due to its scalability and quality. However, inefficiencies such as overproduction, misprints, and excess inventory generate significant paper waste, contributing to greenhouse gas emissions through paper decomposition and energy-intensive reprocessing (Chan and Tay, 2018). While Lean manufacturing has been widely adopted to eliminate Non-Value-Added (NVA) activities, the integration of environmental metrics such as carbon emissions remains limited in practice. Lean Carbon Mapping (LCM) bridges this gap by overlaying carbon emission data onto traditional Value Stream Maps, enabling targeted eco-efficient interventions. This paper investigates the application of LCM in offset printing to optimize paper usage and minimize the associated carbon footprint.

Traditional lean manufacturing tools, such as Value Stream Mapping (VSM), are widely applied in printing industries to identify and eliminate non-value-adding activities (Rai, 2013). However, these tools often overlook the environmental dimension of production. While lean practices improve efficiency, they do not explicitly measure the impact of waste reduction on carbon emissions. To bridge this gap, researchers have introduced Lean Carbon Mapping (LCM), a hybrid tool that integrates lean principles with carbon footprint analysis. LCM enables organizations to simultaneously visualize process inefficiencies, material waste, and associated CO_2 emissions, thereby aligning productivity improvement with sustainability goals(Tang *et al.*, 2016) (Mittal and Shameem, 2024). This study focuses on applying the Lean Carbon Mapping approach in a medium-sized offset printing company to optimize paper usage and reduce its carbon footprint. By systematically analyzing the flow of material and emissions across pre-press, plate making, makeready, printing, and post-press stages, this research demonstrates how LCM can help printing firms achieve substantial reductions in both waste and greenhouse gas emissions.

1.1 **Objectives**

The primary objective of this study is to identify the most carbon-intensive and paper-waste-generating activities within the offset printing process, particularly during setup, production, and post-press operations. By integrating Lean Carbon Mapping (LCM) with traditional Lean tools such as Value Stream Mapping (VSM), 5S, Kaizen, and Standard Working procedures, the research aims to visualize and address both material inefficiencies and associated carbon emissions. The study seeks to quantitatively measure the impact of this integrated approach on reducing paper usage and lowering CO_2 emissions. Ultimately, the goal is to develop a practical and replicable framework for sustainable Lean implementation tailored to the operational realities of the offset printing sector.

This paper seeks to fill this gap by evoking the following research question:
RQ1 How can Lean Carbon Mapping be applied in offset printing industries to systematically reduce paper waste and associated carbon emissions while enhancing process efficiency and sustainability?

2. Literature Review:

Paper is the dominant raw material in offset printing and contributes the largest share to its overall carbon footprint. According to . (Sun *et al.*, 2018), the production of one metric ton of paper results in approximately 950 kg of CO_2-equivalent greenhouse gas (GHG) emissions on average, highlighting its carbon-intensive nature. Furthermore, research by (Zhu *et al.*, 2016)(Amon-Tran *et al.*, 2012) estimated that 1 kg of paper waste generates approximately 1.3 kg of CO_2 emissions, underscoring the environmental burden associated with inefficient paper utilization. These findings stress the critical importance of implementing waste minimization strategies in the printing industry to achieve both economic and ecological sustainability.

Lean manufacturing, derived from the Toyota Production System, focuses on eliminating non-value-adding activities and improving process efficiency (Womack, 2003)(Kumar *et al.*, 2022)(Chan and Tay, 2018). Its application in the printing industry has been reported in several studies, particularly in minimizing waste during pre-press, plate making, and makeready stages. (Rishi *et al.*, 2018) highlighted that lean tools such as 5S, Kaizen, and Total Productive Maintenance (TPM) can significantly reduce downtime and paper wastage in commercial printing presses. Similarly, (Larsson *et al.*, 2025) demonstrated that Value Stream Mapping (VSM) helps visualize bottlenecks and streamline production flows in offset printing. However, these studies focus mainly on productivity improvements without integrating environmental considerations.

Value Stream Mapping (VSM) is a cornerstone lean tool for visualizing flow and eliminating waste; over the past decade it has evolved beyond cost and time to incorporate environmental metrics. Reviews show the trajectory from traditional VSM to smart/sustainable variants that integrate the triple bottom line and digital data capture (Batwara *et al.*, 2023).Early foundational work formalized Sustainable VSM (Sus-VSM)**,** prescribing how to place environmental indicators (e.g., energy, CO_2, water, solid waste) directly on the map. Subsequent case papers demonstrated Sus-VSM's applicability across sectors and proposed step-by-step metrics selection and visualization rules. Related approaches include Environmental VSM (E-VSM)**,** VSM4S**,** and Smart Sustainable VSM, which add methodical PDCA cycles, decision-support, and sensor-driven data. Collectively, these frameworks confirm that adding environmental layers to VSM helps prioritize high-impact improvements (Faulkner and Badurdeen, 2014) (Garza-Reyes *et al.*, 2018).

Several studies quantify carbon emissions on VSM to link lean wastes with CO_2, sometimes labeled "Green-modified VSM," "Carbon-VSM," or "Lean & Green VSM." Methods typically: (i) measure process inputs/outputs, (ii) convert to CO_2 using emission factors, and (iii) visualize hotspots on the map for targeted kaizen. Evidence from manufacturing case studies shows concurrent reductions in lead time and emissions when carbon is made visible at the process box level (Choudhary *et al.*, 2019) .

Lean Carbon Mapping (LCM) is a recent methodological advancement that integrates carbon footprint analysis into the lean mapping process. Unlike traditional VSM, LCM explicitly quantifies the CO_2 emissions associated with each process stage and highlights the carbon-intensive activities . Initial studies in manufacturing sectors, such as automotive and packaging, reveal that LCM can reduce both material waste and emissions by 30–50% (Martínez León and Calvo-Amodio, 2017). However, its application in printing industries remains scarce, presenting an opportunity for research. By embedding carbon metrics into lean tools, LCM enables companies to pursue eco-efficiency, i.e., achieving cost savings while lowering environmental burdens(Bhamu and Sangwan, 2014).

3.Methodology

3.1 Case Study Company

The study was conducted in mid-sized offset printing unit in Tamil Nadu, India. The company consumes 120 tons of paper annually and faces recurring waste during makeready and press stages. A multi-phase case study was conducted in three offset printing firms based in Tamil Nadu. Initial data were collected through site visits, interviews, and analysis of production and utility records. A current-state Value Stream Map (VSM) was developed, followed by a Lean Carbon Map Analysis that included estimating CO_2 emissions based on paper waste, energy use, and reprint volumes. Research framework of the study is shown in figure 1. Lean interventions including 5S, Kaizen, and Standard Work procedures were introduced in areas identified as high carbon and material loss zones.

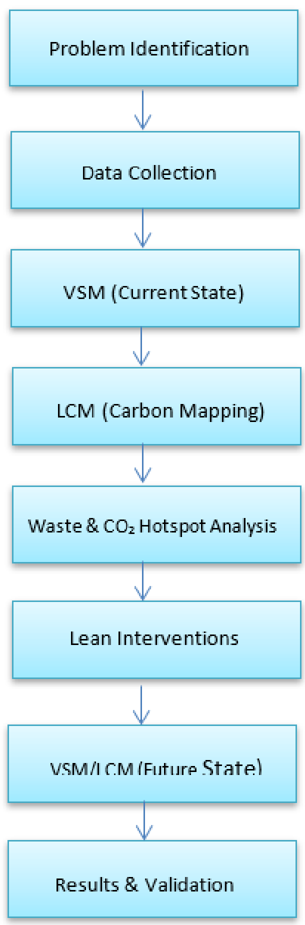

Figure 1. Framework Methodology

4. Data Collection

Data for this study were collected over a three-month period from three offset printing firms in Tamil Nadu, India, using a combination of qualitative and quantitative approaches. On-site observations were conducted to monitor workflows, material handling, and equipment operations, focusing specifically on paper usage during setup, trial printing, and approval stages. Semi-structured interviews and focus group discussions with production managers, machine operators, and quality control personnel provided insights into the causes of paper waste and operational challenges. Historical production records, including paper consumption logs, waste reports, rejected batches, and rework frequency, were analysed to establish baseline performance metrics. Additionally, utility data such as electricity consumption and machine downtime reports were reviewed to estimate energy use and its relation to waste generation. This operational data, along with process times, inventory levels, and transport distances, were used to develop current-state Value Stream Maps. To quantify the environmental impact, carbon emission factors for paper and energy use were sourced from the IPCC Guidelines and the Indian Ministry of Environment, enabling the estimation of CO_2 emissions associated with each stage of the printing process.

4.1 Tools and Techniques Used

Value Stream Mapping (VSM):A current-state VSM is created to map the flow of materials and information across the offset printing process from job order to finished output and Key performance metrics: cycle time, setup time, rework rate, and paper rejection rate.

Lean Carbon Mapping (LCM):An extension of VSM, LCM incorporates carbon emission estimates into the process map. It was instrumental in identifying carbon-intensive activities such as test printing, machine idle time, and paper mismanagement.

5S Implementation: Applied to organize the workplace and reduce handling-related paper damage and Regular 5S audits are conducted to maintain improvements.

4.2 CO_2 calculations

(Emission factor used: 1 kg virgin paper waste → 1.3 kg CO_2e.)

CO_2 from paper waste before LCM

- Pre-press: 5×1.3=6.55 CO_2/day
- Plate Making: 8×1.3=10.48 CO_2/day
- Makeready: 15×1.3=19 CO_2/day
- Printing: 20×1.3=26 CO_2/day
- Post-press: 2×1.3=2.6 CO_2/day

CO_2 from paper waste After LCM

- Pre-press: 3×1.3=3.9 kg CO_2/day
- Plate Making: 5×1.3=6.5 CO_2/day
- Makeready: 8×1.3=10.4 CO_2/day
- Printing: 10×1.3=13.0 CO_2/day
- Post-press: 2×1.3=1.95CO_2/day

5. Results and Discussion:

5.1 Findings before Lean Carbon Mapping

Table 1 presents the baseline scenario of the offset printing process before and after the implementation of Lean Carbon Mapping (LCM). The total paper waste generated was 50 kg/day, corresponding to 65 kg CO_2/day emissions. The printing (20 kg/day) and makeready (15 kg/day) stages were identified as the most waste-intensive. Significant time losses were also observed in the makeready stage (2 hrs) and printing stage (6 hrs), mainly due to repeated test runs, frequent stoppages, and calibration issues. After the implementation of LCM ,Paper waste was reduced to 28 kg/day, corresponding to 35.75 kg CO_2/day. The most notable improvements occurred in the printing stage, where waste decreased by 50% (20 → 10 kg/day), and in the makeready stage, where waste fell by nearly 25% (15 → 8 kg/day). Pre-press and plate-making stages also reported improvements due to reduced design and plate errors.

Table 1. Comparison of time, paper waste, and CO_2 emissions

Stage	Time (hrs)		Paper Waste (kg/day)		CO_2 Emission (kg/day)	
	Before	After	Before	After	Before	After
Pre-press	1	0.8	5	3	6.5	3.9
Plate Making	1	0.9	8	5	10.4	6.5
Makeready	2	1.5	15	8	19.5	10.4
Printing	6	5.5	20	10	26.0	13
Post-press	4	5.4	2	1.5	2.6	1.95
Total	-	-	50	27.5	65	35.75

5.2 Lean Carbon Interventions

In the offset printing process, several lean practices were systematically implemented to reduce waste and improve efficiency. In the pre-press stage, revisions were minimized by introducing a standard template library and applying 5S principles for better workplace organization. Plate-making errors were reduced by adopting a digital imposition system supported with Poka-Yoke, which eliminated manual setting mistakes. During the makeready stage, paper waste was significantly lowered through the use of a color densitometer and continuous improvement (Kaizen), thereby reducing trial prints. Printing stoppages were effectively managed by implementing Total Productive Maintenance (TPM) with a structured weekly maintenance schedule, ensuring higher machine reliability. Additionally, paper inventory waste was minimized through the adoption of a Kanban system with reorder point control, which helped to streamline stock levels and avoid overstocking. LCM interventions were applied using targeted lean tools as shown in (Table 2).

Table 2. Lean Carbon Interventions

Problem	Root Cause	Lean Tool	Action Taken
Frequent revisions	Design errors	Standard Work + 5S	Pre-press template library
Plate errors	Manual imposition	Poka-Yoke	Shifted to digital workflow
High make ready waste	Lack of calibration	Kaizen + Color densitometer	Reduced trial prints
Printing stoppages	Poor maintenance	TPM	Weekly maintenance plan
Overstocking paper	Poor inventory	Kanban	Introduced reorder point system

5.3 Improvements Achieved

Paper waste reduction

Before**:** 50 kg/day After**:** 27.5 kg/day

Absolute reduction**-** Reduction=50−27.5=22.5 kg/day

Percent reduction - % Reduction=22.5/50×100=45%

CO_2 emission reduction (using emission factor)

$$EF=1.3\frac{\text{kg } CO_2}{\text{kg paper}}$$

Before CO_2 **-**50×1.3=65.0 kg/day

After CO_2 =27.5×1.3=35.75 kg/day

Absolute reduction -CO_2 reduction=65.0−35.75=29.25 kg/day

Percent reduction- % Reduction=29.25/65.0×100=45%

Makeready time reduction

From your tables:

Before = 2.0 hours

After = 1.5 hours
Absolute reduction = 2.0 − 1.5 = **0.5 hours**
% reduction = (0.5 ÷ 2.0) × 100
0.25 × 100 = **25%**

The implementation of Lean Carbon Mapping in the offset printing process yielded significant improvements across environmental and operational dimensions. Paper waste was reduced from 50 kg/day to 28 kg/day**,** representing a 45% decrease, while the corresponding carbon emissions declined from 65 kg/day to 35.75 kg/day, reflecting an equivalent 45% reduction. In addition, operational productivity improved, with makeready time decreasing by 25% owing to proactive maintenance measures and a reduction in rework. These results demonstrate the dual benefits of Lean Carbon Mapping in achieving both sustainability and efficiency in printing operations. Figures 2 and 3 present before and after comparisons of paper waste and CO_2 emissions, respectively, and Figure 4 shows the variation in process time across stages as a time-series plot. Value Stream Map of Offset Printing (After LCM) is shown in Figure 5.

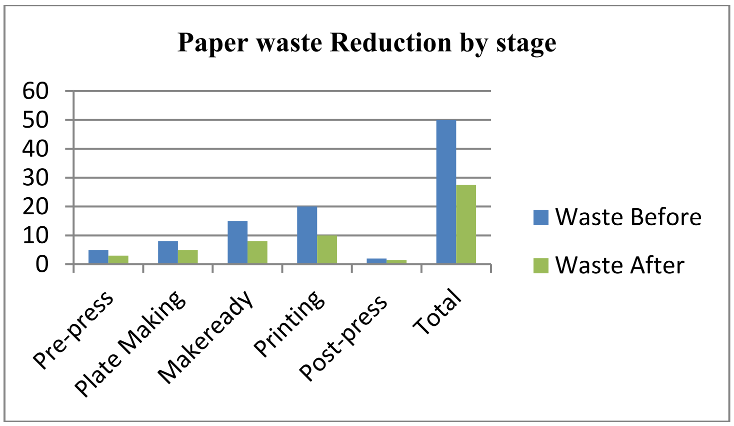

Figure 2. Paper waste before and after implementation of LCM

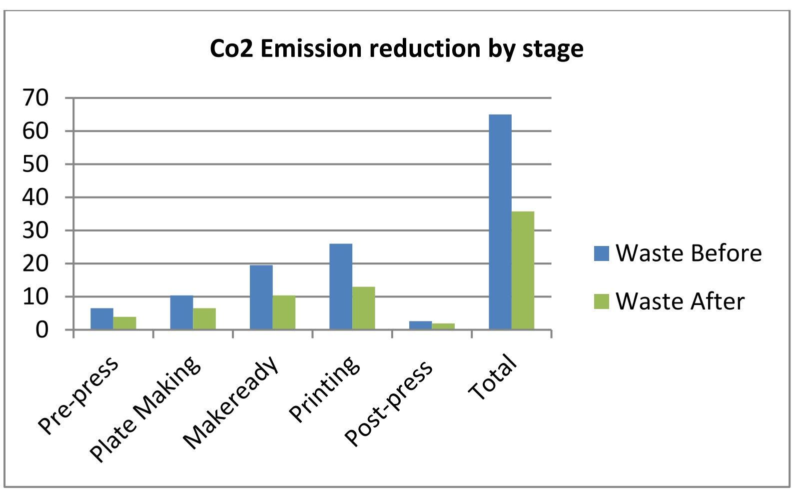

Figure 3. CO_2 before and after implementation of LCM

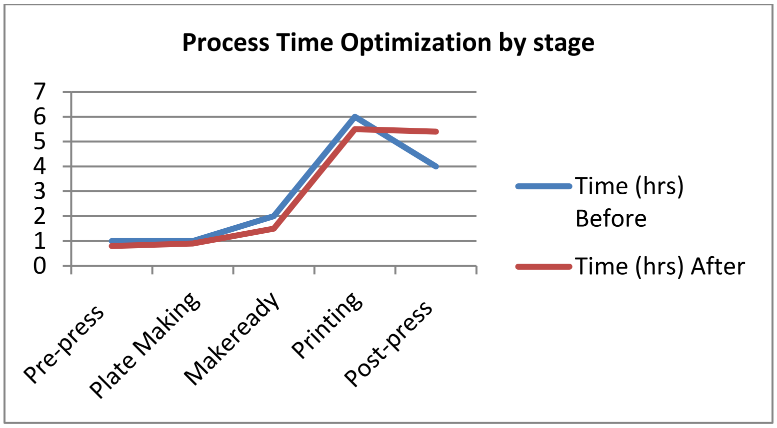

Figure 4. Plot graph based on process time

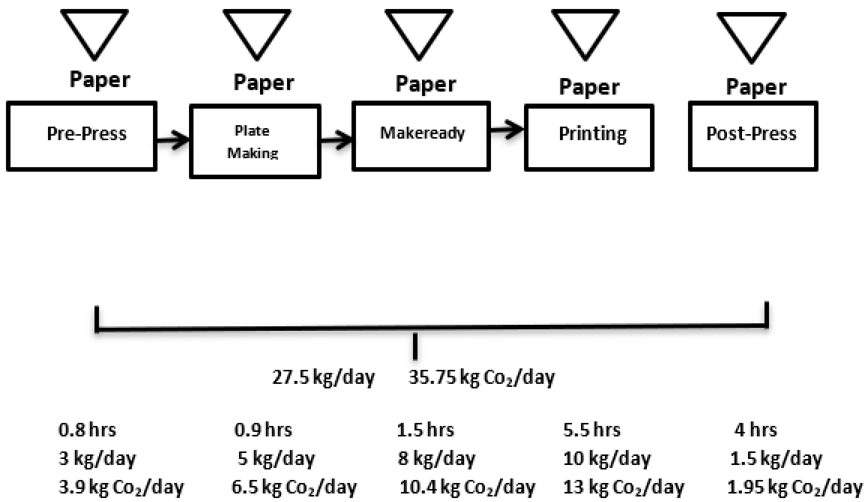

Figure 5. Value Stream Map of Offset Printing (After LCM)

6. Conclusion

The implementation of Lean Carbon Mapping in offset printing demonstrates dual benefits significant reduction in paper waste and a notable decrease in carbon emissions. The case study confirms that environmental sustainability can be effectively embedded into Lean practices through targeted mapping and operational changes. LCM serves as a practical tool for printing firms aiming to improve both economic and ecological performance. This study presents a novel integration of Lean Carbon Mapping LCM with conventional Lean manufacturing tools to address both material efficiency and environmental sustainability in the offset printing industry a sector where Lean-Green applications are yet to be explored to greater depths. Unlike traditional Lean studies that focus solely on operational waste, this research introduces carbon footprint visibility into the value stream, enabling printing firms to target carbon-intensive process steps while reducing paper waste. By quantifying emissions alongside material losses and embedding sustainability metrics into Lean decision-making, the study offers a first of its kind framework for dual impact optimization in commercial printing. The combination of real-world case studies, emission factor analysis, and practical Lean tool deployment distinguishes this research as a pioneering effort toward sustainable lean manufacturing in print production.

The results advocate for broader adoption of Lean Carbon Mapping in resource-intensive industries. For printing firms, this approach enhances both compliance with environmental regulations and operational excellence. Future studies should explore digital integration of LCM using IoT sensors for real-time emission tracking and expand research into other printing technologies such as digital and flexographic systems.

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