

Exploring the Applicability of Green Lean Tools and Methods in Progressive Die Stamping*

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Abstract

The increasing pressure on manufacturing industries to adopt sustainable practices requires the integration of environmental management with traditional efficiency-oriented systems. While Lean manufacturing aims to eliminate non-value-adding activities, it does not explicitly address environmental impacts such as emissions, energy consumption, or resource use. This gap has led to the emergence of the Green Lean concept, which combines Lean and environmental management principles to achieve sustainable manufacturing outcomes. Despite the increasing body of literature on Green Lean, research remains largely conceptual, with limited empirical validation – particularly in energy-intensive sectors like metal forming and progressive die stamping. Addressing this void, the present study aims to identify and analyze Lean tools and methods adapted for sustainability and to evaluate their applicability to progressive die stamping. A literature-based analytical methodology was employed, consisting of four main steps: (1) identifying classical Lean tools; (2) selecting sustainability-oriented adaptations such as Sus-TPM, Green-SMED, and Eco-Design; (3) assessing their potential for implementation in progressive die stamping; and (4) synthesizing the findings into a framework linking Lean methods with sustainability outcomes. The study demonstrates that tools such as Sustainable VSM, Green-SMED, and Sustainable TPM can effectively enhance energy efficiency, reduce material waste, and minimize emissions in stamping operations. The results provide a structured foundation for applying Green Lean principles in metal forming industries and serve as a basis for future empirical research and industrial implementation.

Keywords: Lean manufacturing; Green Lean; Sustainable Manufacturing; Progressive die stamping;

Introduction

The growing demand for environmental responsibility in manufacturing has intensified the need to integrate sustainability principles into traditional efficiency-oriented systems. Lean manufacturing, originating from the Toyota Production System, has long been recognized as a philosophy aimed at eliminating waste (*muda*), improving process flow, and maximizing customer value. However, Lean alone does not explicitly address environmental impacts such as emissions, resource depletion, and energy consumption. In response, the concept of Green Lean – a synergistic framework combining Lean principles with environmental management – has emerged as an effective pathway toward sustainable manufacturing (Dües et al., 2013). Over the last decade, several studies have sought to operationalize this integration through the adaptation of classical Lean tools to sustainability objectives. Examples include Sustainable Value Stream Mapping (Sus-VSM) for visualizing energy and material flows (Faulkner & Badurdeen, 2014), Sustainable Total Productive Maintenance (Sus-TPM) incorporating energy and emission metrics (Crosby & Badurdeen, 2022), and Green-SMED for minimizing

energy losses during changeovers (Leme et al., 2018). Pampanelli et al. (2014) further proposed a Green Lean implementation model integrating life-cycle thinking, sustainability indicators, and continuous improvement feedback. Numerous studies have demonstrated the effective compatibility of combining a green and lean economy under the concept of “Green Lean”, aimed at improving environmental and operational efficiency as well as maximizing a company’s profit and competitiveness (Gholami et al., 2021). Despite these advancements, existing research remains largely conceptual, with limited empirical validation in energy-intensive sectors such as metal forming and stamping.

Progressive die stamping is an energy-intensive and material-sensitive process characterized by sequential forming operations, high press speeds, and considerable scrap generation. Progressive dies are employed to produce complex sheet metal components, enabling multiple forming operations to be carried out within a single tool. The demand for greater geometric variety and higher product quality continues to rise, accompanied by increasing cost pressures across various industrial sectors (Molitor et al., 2025). Previous research on progressive tools has mainly focused on the automated design of punches and dies in progressive dies, aiming to optimize the layout and the number of process stages. The productivity potential of these tools is currently underutilized, as stroke speeds are selected conservatively to prevent tool damage. To address these challenges, Molitor et al. (2025) proposed a data-driven methodology that enables the analysis of sensor signals in progressive dies and the identification of productivity-limiting factors. Borbolla et al. (2024), in turn, investigated sustainable production planning of an industrial progressive die stamping process using Discrete Event Simulation (DES). However, in the context of progressive die stamping, there is still a lack of research focused on process improvement based on the Green Lean concept. Although Lean methods such as 5S, Kaizen, and Single Minute Exchange of Die (SMED) are widely implemented in stamping, their integration with environmental performance metrics remains insufficiently explored. Gholami et al. (2021) emphasize that despite the growing number of publications on the application of VSM for sustainable development, research on this environmentally extended application is still lacking compared to studies on conventional VSM. Moreover, although Lean and Green are strongly correlated, many companies find it challenging to integrate and implement both practices simultaneously, especially when resources are limited (Ng et al., 2015). This highlights the need to systematically assess how Green Lean tools can be applied to minimize energy use, waste, and emissions while sustaining productivity in the area of progressive die stamping. Accordingly, the main aim of this study is to identify and analyze Lean tools and methods adapted for sustainability (1) and to evaluate their applicability to progressive die stamping (2). By conducting a literature-based assessment, it aims to bridge the gap between conceptual Green Lean models and their practical implementation in stamping manufacturing environments.

Research Methodology

The research adopts a literature-based analytical approach to identify, classify, and assess Green Lean tools and methods applicable to stamping. The methodology consists of four main steps:

1. Identification of classical Lean tools from academic literature.
2. Selection of sustainability-oriented adaptations such as Sus-TPM, Green-SMED, and Eco-Design.
3. Evaluation of the potential for implementation in progressive die stamping.
4. Synthesis of results into a framework linking Lean methods with sustainability outcomes.

Applying the described methodology will enable the development of a structured set of Green Lean tools and methods that can support the improvement of production processes in the progressive stamping industry. This will enable companies to consciously select solutions appropriate to the specific process, aimed at reducing energy consumption, material losses and emissions, and improving operational efficiency. From a scientific perspective, this study will contribute to filling the research gap related to the lack of a comprehensive methodology for assessing and selecting Lean-Green tools in the context of metal stamping processes. The results can provide a basis for further research on the integration of Lean principles with sustainable development practices in energy-intensive sectors.

Results

Step one of the methodology described above involved identifying classical Lean tools from the academic literature. These methods are presented in Tab. 1, column 2. Following the step 2 of the methodology, the literature review identified numerous Lean tools and methods that have been adapted to include sustainability criteria. These Green Lean tools demonstrate a clear potential to address the specific environmental challenges present in progressive die stamping. A descriptive summary of the key adaptations is provided below, while a comprehensive framework is presented in Tab. 1. For problem identification, Value Stream Mapping has been enhanced to

Sustainable VSM (Sus-VSM), which integrates environmental metrics like energy, water, and material flows to visualize sustainability performance (Faulkner & Badurdeen, 2014). The extension of VSM with the Carbon-Value Efficiency (CVE) metric, based on a case study of producing metal stamped parts, was presented by Ng et al. (2015). Gholami et al. (2021) propose an advancement of the Green Lean Six Sigma (GLSS) concept through a logically and clearly structured DMAIC-based approach that enables manufacturers to systematically implement e-VSM tools, using the example of electroless nickel plating.

Similarly, the Green Gemba Walk adapts the shop-floor analysis to include checks for environmental wastes, such as media leaks or idle energy consumption (Cherrafi et al., 2019). In the area of process improvement, SMED has evolved into Green-SMED, linking reduced changeover times to minimizing idle energy and startup scrap (Leme et al., 2018). Total Productive Maintenance (TPM) is adapted as Sustainable-TPM (Sus-TPM), incorporating environmental criteria into maintenance pillars to prevent resource losses (Crosby & Badurdeen, 2022). Furthermore, Green-5S extends the classic tool to include waste segregation, recycling, and environmental awareness (Ho, 2014). Finally, in product development, Lean Product Development has been combined with Eco-Design and Life Cycle Assessment (LCA) to optimize blank layout and minimize material waste from the design stage (Dahmani et al., 2021; Luz et al., 2018). Although tools such as 5 Whys and Poka-Yoke are applied in lean/sustainability initiatives, the literature lacks evidence of a dedicated ‘green’ adaptation of these tools specifically designed for environmental performance improvement. The following table (Tab. 1) provides a detailed synthesis of these tools, linking their green adaptations to specific potential applications in progressive die stamping.

Tab. 1 Applicability of Green Lean Tools and Methods in Progressive Die Stamping

Application area	Classic Lean tool / method	Green adaptation – concept and description	Source	Potential application in progressive die stamping
Problem identification	VSM (Value Stream Mapping)	Sustainable VSM (Sus-VSM): extension of the value stream map with environmental metrics (energy, water, waste, emissions) and visual sustainability layers.	(Faulkner & Badurdeen, 2014)	Mapping stamping line energy per batch, material usage, scrap, and cycle time; identifying process stages with the highest environmental impact.
		e-VSM with environmental layer; real-time visualization of energy/utility usage and digital Andon for environmental anomalies.	(Alvandi et al., 2016)	Tracking energy per part, detection of excessive standby, optimization of press parameters.
		A case study involving metal stamped parts is presented to demonstrate how the proposed methodology enhances the Carbon-Value Efficiency (CVE) of the production plant. The current-state CVE-VSM and the future-state CVE-VSM are presented and discussed.	(Ng et al., 2015)	Reduction in production lead time, overall processing time, and carbon footprint, as well as improvement in CVE
	Lean Six Sigma	The present study contributes to the limited body of literature on Green Lean Six Sigma (GLSS) by proposing a logically and clearly structured DMAIC-based approach that enables manufacturers to	(Gholami et al., 2021)	Reducing material waste, lubrication consumption and energy consumption

		systematically implement E-VSM tools, using the example of electroless nickel plating.		
	Gemba Walk	Green Gemba Walk: checklist of '7 environmental wastes' (energy, water, air, chemicals, solid waste, noise, emissions).	(Cherrefi et al., 2019)	Detection of media leaks, unnecessary idle time with running presses, excessive coil movements.
	Ishikawa Diagram	Eco-Ishikawa: addition of environmental branches (energy, materials, utilities, emissions) in cause analysis.	(Malinowska, 2010)	Root causes: die wear, improper lubrication, press setting, coil parameters.
Process improvement	SMED (Single Minute Exchange of Die)	Green-SMED: linking changeover time reduction with minimization of idle energy, start-up waste, and CO ₂ footprint.	(Leme et al., 2018)	Faster die and coil changeovers, fewer trial strokes, shorter warm-up periods for presses and auxiliaries.
	TPM (Total Productive Maintenance)	Sustainable TPM (Sus-TPM): integration of environmental criteria with TPM pillars (Autonomous, Preventive, and Early Equipment Management), including monitoring of energy and fluid losses.	(Crosby & Badurdeen, 2022)	Prevention of press and die failures, use of eco-lubricants, reduction of unplanned downtime and start-up scrap.
	5S	Green-5S: extension of 5S standards with minimization of consumables, waste segregation, recycling, and ergonomic environmental awareness.	(Ho, 2014)	Standardization of lubricants and cleaning agents; visual identification of scrap and recycling flows.
	TOC + Kaizen	Cycle-time reduction for sustainability: shorter cycle time reduces energy and emissions per part under constant power.	(Goyal et al., 2022)	Optimization of speed and lubrication without quality loss.
Flow and Supply Chain Management	Just-In-Time (JIT)	Green-JIT: balancing inventory reduction with transportation and carbon footprint minimization; supplier synchronization and consolidation.	(Singhal et al., 2025)	Material deliveries aligned with production sequence and setup plan.
	Lean Supply Chain	Green Supply Chain (GSCM): Lean-based practices extended to waste and emission reduction across the supply chain	(Hossain et al., 2023)	Closed-loop recycling of stamping scrap, optimized coil packaging.
Product development	Lean Product Development	Lean Eco-Design: Eco-Design combined with LPD	(Dahmani et al., 2021)	Adjusting blank layout, reducing bridges, optimizing trimming allowance

		Lean Product Development + Life Cycle Assessment (LCA)	(Luz et al., 2018)	Optimization of material utilization, reduction of embodied energy in tool manufacturing
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Based on the above-presented analysis, a synthetic conceptual framework was developed, linking classic Lean methods with their “green” adaptations and potential sustainability effects in the progressive die stamping. The proposed approach allows for the linking of specific Green Lean tools with application areas such as problem identification, process improvement, flow and supply chain management, and product development. The results were summarized to facilitate practical application by companies to reduce energy consumption, limit material losses and emissions, and improve operational efficiency. The developed framework can serve as a reference point for further empirical research and implementation of the Green Lean concept in the metal forming sector.

Conclusions

This study successfully identified and analyzed the integration of Lean manufacturing principles with sustainability objectives, confirming the viability of the Green Lean approach. The literature-based analysis provided a structured overview of how classical Lean tools have been adapted to address critical environmental performance indicators.

The primary contribution of this research is the systematic assessment of these Green Lean tools' applicability to progressive die stamping – an energy, material-intensive process. The findings confirm that tools such as Sus-VSM for mapping energy and material flows, Green-SMED for minimizing energy losses during changeovers, and Sus-TPM for managing resource consumption have direct and practical potential. Implementing these methods can lead to tangible benefits in stamping operations, including reduced energy consumption per part, lower scrap rates, and minimized auxiliary resource usage.

As outlined in the methodology, this research provides a foundational framework. The logical next steps for future work should focus on moving from theoretical applicability to empirical validation. This includes:

1. Conducting an in-depth industrial case study to implement the identified Green Lean tools within a real progressive die stamping environment.
2. Developing a quantitative model to measure the precise impact of these tools on both operational (e.g. OEE, changeover time) and environmental (e.g., kWh/stroke, scrap-to-product ratio) metrics.
3. Exploring the integration of these tools with Industry 4.0/5.0 technologies, such as real-time energy monitoring (e-VSM), to further enhance sustainable performance.

This paper serves as a practical guide for manufacturers in the metal forming sector and a starting point for further academic research into the empirical validation of Green Lean in high-energy manufacturing.

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