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Integrating life cycle assessment with lean assessment matrix: A framework for sustainable automotive manufacturing evaluation

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Abstract

Automotive manufacturers face growing pressure to improve efficiency while reducing environmental impacts, but standard waste assessment tools largely overlook energy use and material losses. This study develops an integrated evaluation framework that combines a lean assessment matrix with life cycle based environmental indicators to support waste prioritization in automotive manufacturing. A rapid review of 27 relevant articles informs the framework design, resulting in a matrix that links process wastes to non-value added activities, root causes, and five performance indicators: economic performance, process flow, quality, energy use, and material and waste generation. A scoring system based on a discrete rating scale is proposed to convert heterogeneous operational and environmental data into severity scores and priority ranks for each waste type. This enables comparison of improvement options on an everyday basis that reflects both productivity and environmental impact. The framework extends lean assessment beyond traditional operational measures and provides a structured basis for sustainability-oriented decision-making in automotive manufacturing.

Keywords

Sustainable manufacturing, Automotive industry, Life cycle assessment, Lean assessment matrix, Performance evaluation, Waste prioritization

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Introduction

The accelerating transition toward sustainable industrial practices has introduced new challenges for the automotive manufacturing sector, which must balance economic performance and environmental integrity [1]. Automotive manufacturers face pressure not only to improve cost efficiency, quality and delivery performance, but also to reduce energy use, emissions and waste generation [2]. Under limited improvement resources, the key issue is therefore not only process optimisation but also the selection of improvement priorities with the greatest combined operational and environmental impact. Prioritisation approaches dominated by operational indicators can overlook the environmental consequences of non-value added activities, such as additional energy use from rework or material losses from scrap [3], and may lead to improvement portfolios that are misaligned with sustainable manufacturing objectives in energy and material intensive operations.

To address operational performance challenges, many studies apply Lean Manufacturing to identify and reduce waste. At the assessment and prioritisation level, the Lean Assessment Matrix (LAM) combines information on waste types, root causes and key performance indicators (KPIs) to derive severity levels and improvement priorities. This structured assessment helps organisations to concentrate interventions on critical areas. However, recent studies show that LAM applications still focus mainly on operational KPIs, while environmental aspects are often either omitted or represented through inconsistent proxies [4]. As a result, waste categories with similar cost or time impacts can have very different environmental burdens. In parallel, Lean and Green Manufacturing aims to align waste elimination with resource efficiency and environmental performance [5], yet review studies report persistent limitations in environmental measurement: indicators are partial, context-specific and poorly connected to shop-floor prioritisation mechanisms [6], [7]. Life Cycle Assessment (LCA) offers a rigorous framework to evaluate environmental impacts based on inventories of material and energy flows[8], [9], but its results are often produced as standalone analyses and are rarely translated into operational tools that shop-floor teams can use.

Although many studies discuss lean green manufacturing, most still treat life cycle assessment (LCA) and lean tools separately. Some works use LCA based indicators or combine process-level LCA with performance evaluation in manufacturing [10], [11], [12], [13], but the results usually remain separate and are not embedded in daily waste prioritization on the shop floor. To date, there is no concise assessment matrix that integrates LCA informed indicators into a Lean Assessment Matrix for waste evaluation in automotive plants. This study therefore proposes a conceptual framework that keeps the core structure of LAM while adding environmental indicators derived from LCA and life cycle inventory (LCI), so that cradle to gate environmental information can be translated into shop floor improvement priorities.

This study aims to develop an integrated evaluation framework for automotive manufacturing that links operational improvement prioritization with environmental impact considerations. Using a Rapid Review (RR) approach via the Dimensions.ai platform, the study synthesizes relevant evidence to formulate the proposed assessment matrix, guided by explicit selection criteria. The primary methodological contribution is the development of procedures to normalize LCA/LCI indicators into LAM-compatible scores and to specify an evaluation instrument that can support systematic sustainability-oriented improvement planning in automotive manufacturing contexts.

Method

Rapid review procedure

The framework integrating LCA and the Lean Assessment Matrix was informed by a rapid literature review (RR). RR was selected because it allows a focused synthesis of evidence within a limited time frame while maintaining key elements of systematic review rigour [14], [15]. The review examined how lean assessment matrices can be extended with LCA informed indicators to support waste prioritisation in automotive manufacturing.

The search was conducted in the Dimensions.ai database, which integrates journals, conference proceedings and other scholarly outputs. A Boolean query combining terms for life cycle assessment, environmental performance, lean assessment matrix, key performance indicators and automotive/manufacturing was used. Filters were applied to restrict results to publications from 2021–2025, in the fields of engineering or manufacturing, and to documents accessible as full text. This search returned 275 records.

Screening followed a stepwise procedure summarised in Table 1. Titles and abstracts were first checked to remove studies that did not substantively discuss lean performance evaluation (Step 1) or that did not use measurable performance indicators (Step 2). In Step 3, studies addressing concepts equivalent to a lean assessment matrix were retained even if different terminology was used. Step 4 excluded articles that did not provide any interface for integration with LCA. Finally, in Step 5, the remaining records were assessed in full text to identify 27 core articles that most directly informed the design of the LCA–LAM framework. These articles were then synthesised into thematic clusters, as reported in Table 2.

Table 1. Exclusion criteria of RR methods to build the framework of LCA-LAM in automotive industry

Step	Selection Criteria	*n* articles*
Dimensions.ai	Selected prompt and filters	275
Exclusion Step 1	Relevance of general context	210
Exclusion Step 2	Presence of KPI in Lean Matrix	130
Exclusion Step 3	Approach of structured assessment in Lean	80
Exclusion Step 4	Linkage with LCA or environmental aspect	45
Exclusion Step 5 (Final Step)	Integration of LAM, LCA or environmental aspect and environmental indicator (KPI)	27

(*): *n* articles shows the amount of articles which pass the selection criteria and are included for the next selection steps.

Matrix formulation procedure

The integrated Lean–LCA Assessment Matrix was developed in three steps: evidence extraction, conceptual mapping, and mathematical specification. From the 27 articles selected in the rapid review, we extracted information on (i) waste and performance constructs used in lean assessment tools, (ii) environmental KPIs and LCA boundaries in manufacturing studies, and (iii) scoring and weighting schemes and data availability at the shop floor level. These findings were grouped into the thematic clusters in Table 2 and used as design requirements for the framework.

In the second step, evidence from the literature was translated into the matrix structure. The nine waste types, non-value added activities, and root causes were adapted from existing LAM formulations, while the KPI dimension was extended with two environmental categories (energy or carbon, and material or waste) consistent with cradle to gate LCA indicators. The LCA scope was aligned with the production stages in Figure 1, and mapping rules were defined that link each waste type to its root causes, operational KPIs, and LCA based indicators.

In the third step, the scoring and weighting scheme was specified. A common three-level rating scale (0,1,2) was adopted for all KPIs, as shown in Table 4, and waste type weights WT_i were defined to represent the relative importance of each waste category. The performance ratings P_{ij}, weights, and root cause occurrence levels O_j were then combined to calculate the severity level S_i and the Aggregate Waste Number AWN_i according to Eqs. (1)–(3).

Results and discussion

This section presents the results of the rapid review. It consolidates the selected studies into thematic clusters that form the foundation of the proposed LCA-integrated Lean Assessment Matrix (LAM) framework. In this study, the term results refers to the outcomes of the literature synthesis, namely the final set of selected articles and their thematic grouping. Table 2 summarizes the clusters and the key evidence extracted from the literature, while the Design implications for the proposed framework are discussed further in the Discussion section. Accordingly, the Results section remains descriptive and evidence-based, whereas interpretation is provided in the subsequent section

Summary of articles selected

This subsection presents a thematic analysis of the selected literature. As shown in Table 2, articles are grouped into clusters, with supporting evidence extracted from each cluster informing the design implications for the proposed LCA-integrated LAM framework

Table 2 summarises the main themes from the literature. Three patterns are particularly relevant for the LCA–LAM design. First, environmental KPIs should be selected systematically, with clear life-cycle or process relevance, and combined using weighting, scoring, and ranking methods for prioritisation. Second, although lean and green goals often overlap, environmental measurement at the shop floor level is fragmented and only weakly connected to daily improvement routines, especially in automotive plants. Third, data-driven assessment and intralogistics studies show that existing production, energy, safety, and logistics data can be repurposed to support environmental evaluation, including energy use, scrap, and internal material flows. These insights inform the KPI structure (K1–K5), the normalisation of LCA indicators to LAM scores, and the cradle-to-gate assessment scope adopted in the proposed framework.

Table 2. Literature for the proposed LCA integrated lean assessment matrix framework

Cluster	Authors	Evidence	Implication for Integrated LAM-LCA
LCA informed KPI Selection	[10], [11]	Environmental KPIs should be chosen systematically and reflect lifecycle/process impacts	Use flexible KPI slots, but require energy/carbon and material/waste (LCA-informed) and normalize to LAM scores
Prioritization methods	[12], [16], [17], [18]	Sustainability evaluation commonly uses weighting–scoring–ranking.	Justify LAM as the ranking engine; integrate LCA indicators to strengthen environmental scoring.
Lean–Green alignment and measurement limits	[17], [18]	Lean–green goals align, but environmental metrics are often partial/inconsistent and weakly linked to shop-floor priorities.	Motivate the need for a consistent environmental layer inside LAM (via LCA-informed KPIs).
Integrated improvement paradigms	[19], [20]	Integrated paradigms exist, but indicator sets vary widely across contexts.	Position iLAM–LCA as a standardizable evaluation backbone with adaptable KPIs and fixed LCA minimums.
Automotive lean–green evidence	[21], [22]	Automotive studies confirm simultaneous operational and sustainability pressures.	Support automotive relevance and justify focusing on energy/emissions and material loss.
Data-driven assessment and review syntheses	[23], [24]	Data-driven approaches and review syntheses enable structured, implementable assessment frameworks.	Support feasibility: shop-floor/EHS data can feed LCI, then be normalized into LAM scores.
Automotive intralogistics	[22], [25]	Internal logistics also contributes to energy use and packaging/waste	Define scope as plant gate-to-gate (production and intralogistics) using the same LCA KPI categories and LAM ranking.

Production process in automotive industry

To incorporate the LCA concept into this framework, it is essential to understand the main production routes used in the automotive industry. This study's LCA focuses solely on the production stage, using a cradle-to-gate boundary. Casting, forging, machining, stamping, and other shaping processes run in parallel for different component families before feeding into sub-assembly and final assembly lines. Figure 1 shows a simplified view of these key routes and their typical flow from design and component manufacturing to assembly.

In general, production starts with design and prototyping, where the required strength, stiffness, and surface quality of components are specified [26]. Casting converts liquid metal into near net shape parts and is widely used because it is cost effective and dimensionally accurate [27]. Forging then improves mechanical properties by plastically deforming metal into the desired shape through repeated blows. Machining removes material to achieve tight tolerances and functional surfaces [28]. Stamping forms sheet metal into body and structural parts in high speed presses, often generating offcut scrap [29]. Welding joins a wide variety of components and ensures structural integrity, safety, and durability [30]. Finally, the assembly process brings together the manufactured parts into complete vehicles in a sequenced flow designed to optimise performance, minimise production time, and assure product quality [31].

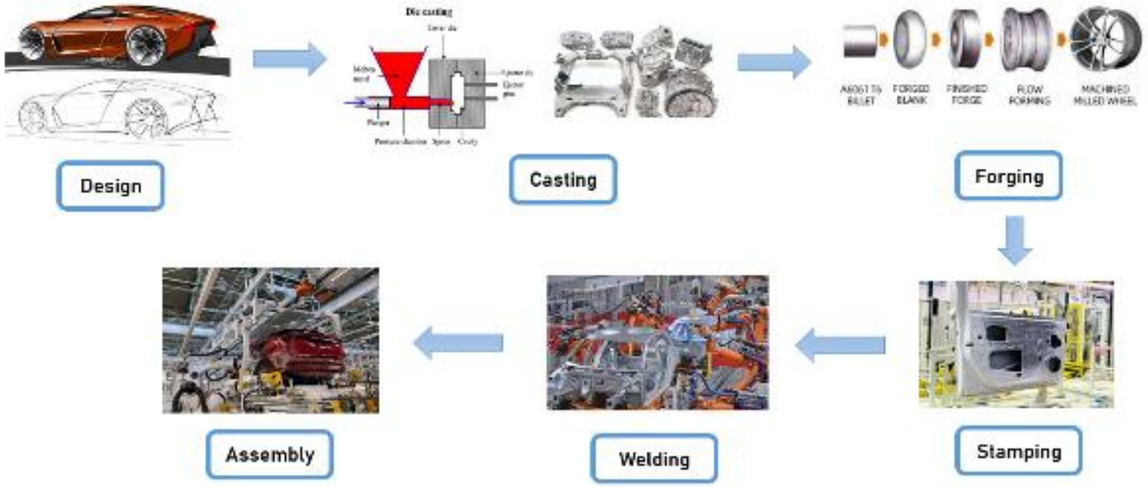

Figure 1. Simplified production process routes in the automotive industry (parallel casting, forging, machining, and stamping feeding into final assembly)

Integrated lean-LCA assessment framework

Table 3. Integrated lean-LCA assessment matrix for waste prioritization

		Root Source of Waste			KPI							
Waste Type	**Non Added Value Activity**	**S1**	**Sn**	**Waste Type Weight**	**K1**	**K2**	**K3**	**K4**	**K5**	**Severity Level of Waste**	**Aggregate Waste Number**	**Priority Rank of Waste**
Defect	*W1*	I_{ij}		WT_i	P_{ij}					S_i	AWN_i	1
Overproduction	*W2*											
Waiting	*W3*											
Transportation	*W4*											
Over Inventory	*W5*											
Motion	*W6*											
Over Processing	*W7*											
EHS	*W8*											
Underutilized People's Skill	*W9*											
Occurrence level of Root Source of Waste j		O_j										
Aggregate Cause		AC_i										
						Lean / Operational KPIs		LCA-Based KPIs				

Based on the preceding discussion, the proposed Lean–LCA integration is operationalized through the assessment matrix presented in Table 3. Each Lean waste type identified in the automotive manufacturing process is linked to its corresponding non-value- added activities and root sources of waste (S_1–S_n), and assigned a waste-type weight (WT_i). The impact of each waste is then evaluated using five key performance indicators (K1–K5): K1–K3 capture economic, flow, and quality-related Lean or operational performance, while K4–K5 represent LCA-based environmental performance related to energy/carbon and material/waste. These indicators are combined to determine the severity level (S_i), the aggregate waste number (AWN_i), and the final priority rank for each waste type, thereby enabling waste-reduction decisions that are both operationally efficient and environmentally sustainable.

The matrix arranges waste types in the rows and the sources and impacts of waste in the columns. For each waste type W_i, the second column lists the related non-value-added activities, followed by the root sources of waste, their occurrence level O_j, and the waste type weight WT_i. The KPI block then scores the impact of each waste type on K1–K5, where K1–K3 represent economic, flow, and quality performance, and K4–K5 represent LCA based environmental performance related to energy or carbon and material or waste. These scores are aggregated into the severity level S_i, which is combined with WT_i, and the root cause occurrence to calculate the Aggregate Waste Number AWN_i and the final priority rank. In this way, the matrix links each waste type to its causes, its operational and environmental effects, and its integrated improvement priority. In shaping operations (casting, machining, forging, stamping), material losses such as machining chips, sheet-metal scrap, and solidified gating systems are mainly tracked with K5, along with defect, overprocessing, and EHS waste types. This approach ensures that shaping-process waste appears in the matrix as part of the material and waste performance dimension.

Table 4. Rating scale for KPI impact

Rating	Effect	Description
0	No impact	No noticeable effect on achieving the KPI target
1	Low impact	Small deviation from the KPI target
2	Medium impact	Clear deviation from the KPI target / noticeable loss

All KPIs in the LCA–LAM framework are evaluated using a common ordinal rating scale, as summarised in Table 4. The quantitative indicators for each KPI (cost, flow, quality, energy/carbon, and material/waste) which are typically obtained from process level LCA calculations, energy bills with emission factors , and scrap or waste records, are first collected and then converted into a discrete rating from 0 to 2, where 0 indicates no impact on the KPI target, 1 indicates a low impact, and 2 indicates a medium impact. The boundaries between these classes are defined based on internal targets, historical data, or expert judgement. This procedure translates heterogeneous operational and environmental indicators into comparable scores P_{ij}, which are subsequently aggregated into the severity level S_i and the Aggregate Waste Number in Eqs. (1)–(3).

$$AWN_i = WT_i S_i \sum O_j I_{ij} \tag{1}$$

$$AC_i = O_i \sum S_j I_{ij} \tag{2}$$

$$Si = \sum_{j=1}^{k} P_{ij} \quad i = 1, \ldots, p \tag{3}$$

Where :

i : Index of waste type (I = 1 , … ,p)
j : Index of root source of waste (j = 1, … , n)
k : index of KPI (k = 0, … , 2)
AC_i : *Aggregate Cause index of waste type i* (AC)
AWN_i : *Aggregate Waste Number of waste type i* (AWN)
WT_i : *Weight assigned to waste type i*
O_j : *Occurrence level of root source of waste j*
S_i : *Severity score of waste type I, obtained from the selected KPIs (K1-K5)*
I_{ij} : *Impact value of root source of waste j to waste i*
P_{ij} : Performance score of waste type *i* on KPI *j*

The rapid review and the proposed LCA–LAM framework show that operational and environmental performance can be evaluated in a single structure for automotive manufacturing. By embedding LCA informed KPIs (K4–K5) into the Lean Assessment Matrix, waste reduction decisions can consider both efficiency and environmental impact, not only cost, flow and quality.

The clusters in Table 2 justify the main design choices. Studies on LCA-informed KPI selection stress that environmental indicators must match process boundaries and decision needs, and that too many indicators make implementation difficult. This supports the choice of two environmental dimensions, energy/carbon and material/waste, as K4 and K5. Evidence on prioritisation methods confirms that weighting and scoring–ranking are common and practical; the framework keeps the original LAM logic (weights, severity and aggregate waste numbers) and simply extends the KPI set from K1–K3 to K1–K5.

Work on lean green alignment and measurement limits shows that environmental metrics are often fragmented and loosely linked to improvement routines. Normalising LCA-based indicators into LAM-compatible scores directly addresses this issue. Energy use, emissions, scrap mass and other waste-related data can be converted into dimensionless scores that are comparable with operational KPIs, so trade offs and environmental “blind spots” become visible when ranking wastes. Data-driven assessment and intralogistics studies also indicate that the necessary data already exist in most plants; the framework therefore defines KPI categories rather than fixed indicators so that each site can plug in its own measurements.

Theoretically, the framework links lean thinking and life cycle perspectives by mapping LCA informed indicators to lean waste types and including them in the same severity calculation. Waste is no longer seen only as cost or time loss but also as unnecessary resource use and emissions. Managerially, the matrix offers a simple visual tool that supports discussions among production, quality, maintenance and environmental staff.

Aggregate waste numbers and priority ranks help managers justify projects with high environmental relevance and align lean initiatives with sustainability goals.

This study has several limitations. The framework is conceptual and based on a rapid review; it has not yet been tested in real automotive plants, so the effort required for data collection and normalisation remains uncertain. The environmental layer is limited to two impact categories, which simplifies use but may omit other relevant impacts in some contexts. Future research should apply the LCA–LAM framework in case studies, refine the KPI set and normalisation rules, test the sensitivity to weight choices and explore adaptations for other life-cycle stages or other manufacturing sectors.

Conclusion

This study set out to develop an integrated evaluation framework that links Lean Assessment Matrix (LAM)–based waste prioritization with life-cycle-informed environmental performance in automotive manufacturing. Drawing on a rapid review of 27 studies, the research synthesised evidence into thematic clusters that guided the design of an extended LAM structure. The resulting LCA–LAM framework preserves the original LAM logic waste types, root causes, weighting, severity, and ranking while extending the KPI dimension from purely operational indicators (cost, flow, quality) to a combined set that also captures energy and carbon/carbon and material/waste impacts.

Conceptually, the framework advances knowledge by showing how LCA based indicators can be normalised into LAM-compatible scores and mapped to lean waste categories. This provides a holistic view of waste, including economic inefficiencies, resource intensity, and emissions. From a managerial perspective, the LCA–LAM matrix offers a structured, adaptable tool that leverages shop-floor and environmental data to prioritise improvement projects based on operational and environmental benefits, aligning productivity and sustainability goals in automotive plants.

The conclusions of this study remain subject to several limitations. The framework is developed at a conceptual level and has not yet been empirically validated, and the environmental layer is simplified to two key dimensions, which may not fully represent all impact categories. These constraints, however, open clear avenues for future research. Empirical case studies in different automotive plants are needed to test and refine the framework, including KPI choices and normalisation procedures, and further work could extend the approach to other life-cycle stages and manufacturing sectors. Overall, the proposed LCA– LAM framework provides a basis for more consistent, sustainability-oriented prioritisation in automotive manufacturing.

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