

A PROCESS-MINING-DRIVEN FRAMEWORK FOR AUTOMATED CO₂ EMISSION TRACKING

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Abstract

Rapid industrialization and climate change have created an urgent need for accurate, automated, and scalable carbon emission monitoring systems. Conventional methods for tracking CO₂ emissions are often fragmented, manual, and error-prone, limiting the reliability and transparency of environmental reporting. Organizations face challenges in integrating disparate operational data, handling missing emission factors, and generating actionable insights, which hampers effective sustainability decision-making. To address these challenges, this study proposes a Process-Mining-Enabled Framework for Automated CO₂ Emission Tracking that integrates process intelligence with environmental analytics while ensuring confidentiality, adaptability, and reproducibility. The framework leverages operational datasets combined with emission factors from established public or scientifically validated databases and incorporates user inputs for processes with unknown CO₂e coefficients. End-to-end workflows are reconstructed using process mining techniques, enabling the identification of high-emission stages, bottlenecks, and inefficiencies. Automated action flows support continuous data ingestion, anomaly detection, threshold alerts, and near -real-time emission calculation, providing a dynamic and scalable solution for monitoring carbon emissions across complex industrial processes. This approach improves emission-tracking efficiency, reduces manual reporting effort, and enhances the accuracy and reliability of environmental metrics. Its flexible design allows deployment across diverse organizational contexts, supporting transparent, audit-ready, and reproducible carbon-footprint assessments. By combining process mining, predictive analytics, and automated environmental monitoring, this study presents a novel, integrative methodology that bridges digital process intelligence with sustainability goals.

Keywords: Process Mining, CO₂ Emission Tracking, Sustainability Analytics, Carbon Footprint Estimation, Workflow Automation, Emission Factor Mapping.

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1. Introduction

Environmental sustainability has transitioned from merely being an issue of concern into a fundamental function of all organisations. While businesses have large amounts of data about their operations through procurement and supply chain activities, the way they collate that data for the purpose of calculating emission levels is rarely consistent. Carbon accounting processes often rely on disparate data sources and manual consolidations to create carbon accounting reports, which makes it time-consuming, unreliable, and less useful for decision makers. Although innovations in

research have greatly advanced environmental analytics and process intelligence, they have yet to be incorporated into practical carbon accounting systems. As a result of this gap, organisations often report carbon footprints which are based on estimates rather than embedded in the environmental operations of the organisation. While several researchers have conducted studies on using data from IoT (Internet of Things) sensors, blockchain technology, and predictive methods, those methodologies require extensive, real-time information that most enterprise systems and supply chains are not able to collect and maintain. As a consequence of these issues, businesses face delays in reporting their emissions data, lack of transparency regarding emission reporting, and difficulties in verifying their emission factors without exposing proprietary data. A new framework is suggested to fill in the gaps that exist in today's carbon accounting processes by employing an integrated approach that combines the use of process mining technologies, Category-based Computerised CO₂ Monitoring, and Per Centile-based Procurement Alerts. The proposed framework is designed to achieve scaling, reproducibility, and more reliable incorporation of environmental sustainability into organisational processes.

2. Literature Review

Advances in process mining and automated carbon accounting have impacted operations and the environment; however, these two fields developed as independent streams and have not experienced a strong integration of process intelligence with real-time carbon monitoring. The development of process mining has improved the means for modeling and predicting workflows, as well as monitoring conformity with various controls, through such advances as OCPM. The OCPM created by van der Aalst permits business object interaction analysis, but traditional process mining techniques use carbon emissions as external annotation rather than as an automatic property.

Applied studies using technologies, such as deep learning for anomaly detection in manufacturing (Mannhardt et al) or mining in pharmaceutical focused on resilience (Park et al), provide greater operational transparency. However, they do not incorporate sustainability metrics into the analytical framework. The early work on Green Process Mining (Bolt et al) used the principle of attaching energy consumption at an event level to specific activities using static coefficients to illustrate feasibility but cannot yet provide sufficient granularity to evaluate Scope 3 emissions at a material or supplier level.

Similarly, economic audit and control frameworks developed for SAP (Jans et al) provide an overview of the financial controls used but fall short of providing a broad-based environmental perspective. Fragmentation within automated carbon accounting continues alongside other aspects of digital transformation. High-resolution methods, such as machine learning on sensor data (Wiedemann et al) or blockchain-IoT tracking of supply chains (Kumar et al), provide precise estimates but require infrastructure-intensive systems. Macroeconomic models, like multi-region input-output analyses (Huang et al), offer broad coverage but cannot evaluate carbon inventories at the procurement level. Product-level machine learning models (Stadler et al) depend on complete bills of materials, which are often unavailable in enterprise resource planning systems. A major challenge across all methods is the availability and consistency of emissions factors. Imputation methods (Li et al) perform best in data-rich environments, while cross-database comparisons reveal substantial variability for identical materials (Schmidt et al). Operational challenges for integrated approaches include delays from batch ETL pipelines (Fernández et al), weaknesses in automated report extraction (Moreno et al), and reliance on blockchain-based

carbon ledgers that require fully developed digital twins (Zheng et al). Validation methodologies for carbon accounting systems in resource-constrained environments remain largely unexplored. Although synthetic event log generation has been applied in financial fraud detection (Müller et al.), similar approaches have not been systematically extended to procurement or environmental analytics. Digital-twin-based LCA simulations (Chen et al.) rely on sensor-intensive manufacturing environments and do not adequately capture the relational complexity of procurement transactions, supplier networks, or material hierarchies. Collectively, these limitations indicate a clear research gap: existing approaches lack embedded carbon semantics, dynamic emission factor management, near-real-time integration, and reproducible validation under data access constraints. Addressing this gap requires a unified, process-aware framework that integrates automated CO₂e estimation directly within operational workflows while supporting scalability, auditability, and deployment in sandbox-compatible enterprise environments—an objective pursued by the proposed work.

3. Methodology

This study proposes a reproducible, modular, and sandbox-compatible framework that integrates process mining with automated CO₂e estimation to enable near-real-time carbon monitoring at the transaction level. The framework is designed to address key limitations identified in existing research, including static emission factor handling, batch-oriented integration architectures, and the absence of embedded carbon semantics in process mining models. By operating entirely within a controlled sandbox environment, the methodology ensures data confidentiality while remaining transferable to enterprise production settings.

3.1 System Architecture

The proposed architecture comprises four interconnected layers: data ingestion, emission factor resolution, process mining integration, and automated alerting. Operational procurement data is ingested as CSV files into the Celonis sandbox environment using ML Workbench (MLWB), enabling controlled experimentation, reproducibility, and compliance with restricted data access requirements commonly observed in enterprise environments. Where CO₂e values are already present in the ingested dataset, they are directly merged into the processing pipeline. In cases of missing emission information, the framework dynamically retrieves emission factors from external providers such as ClimaTiq via secure API calls. This hybrid architecture ensures data completeness while avoiding the rigidity and latency associated with traditional batch-based ETL pipelines.

3.2 Emission Factor Enrichment and Confidence Scoring

To achieve comprehensive and reliable CO₂e estimation, the framework employs a hybrid emission factor enrichment strategy. Internally curated, CSV-based emission factors are prioritized due to their contextual relevance and higher organizational trust. When internal values are unavailable, emission factors are retrieved from external databases and augmented with a confidence score computed based on parameter completeness, material specificity, and data provenance. This confidence-aware enrichment mechanism directly addresses known challenges related to emission factor inconsistency and uncertainty, enabling transparent and auditable carbon estimation without manual intervention.

3.3 Process Mining and Carbon Attribution

Following emission factor enrichment, the dataset is transformed into an event log suitable for object-centric process mining. Procurement activities, materials, suppliers, and cost centers are modelled as interconnected objects, with CO₂e values embedded as intrinsic attributes of the

process rather than as external annotations. This design enables trace-level, activity-level, and material-level carbon analysis, facilitating the identification of emission-intensive paths, structural bottlenecks, and operational inefficiencies. By integrating carbon metrics directly within process models, the framework overcomes a key limitation of conventional process mining approaches, which typically lack native environmental semantics.

3.4 Threshold Monitoring and Automated Alerts

Organizational sustainability targets are operationalized through predefined CO₂e thresholds applied at the transaction level. The system performs continuous near-real-time evaluation of emissions against these thresholds, and when exceedances occur, an automated Celonis Action Flow triggers immediate email notifications to relevant procurement or sustainability stakeholders. This mechanism enables timely intervention and supports proactive decision-making, in contrast to traditional batch-based reporting approaches that delay the identification of emission anomalies.

3.5 Simulation-Based Evaluation

Due to sandbox environment constraints, the framework is validated using synthetically generated procurement event logs that simulate realistic distributions of procurement volumes, material categories, supplier characteristics, and emission variability. These synthetic datasets preserve the structural and statistical properties of real-world procurement processes, enabling reproducible evaluation without exposing sensitive operational data. Evaluation metrics include emission factor resolution success rate, processing latency, anomaly detection effectiveness, and alert responsiveness. This simulation-based validation approach reflects common industrial practice for early-stage sustainability system development and demonstrates that the proposed framework can scale to enterprise-level scenarios while remaining deployable under restricted data access conditions.

4. Contributions of the Proposed work

Unlike conventional carbon accounting approaches that function as detached analytical layers, the proposed framework embeds carbon intelligence directly within operational workflows, enabling near-real-time, process-aware emission monitoring in procurement processes. The framework introduces a sandbox-compatible, simulation-based data pipeline that supports SAP-oriented deployment scenarios while enabling reproducible validation under restricted data access conditions. Through object-centric process mining, CO₂e emissions are directly linked to procurement activities, materials, and suppliers, allowing emission-intensive process paths to be identified with greater precision than aggregate accounting methods. Sustainability targets are operationalized through automated threshold monitoring using Celonis Action Flow, triggering near-real-time alerts for high-emission activities. In addition, the framework establishes a unified and reusable data model within ML Workbench, ensuring auditability and seamless downstream integration. Simulation-based evaluation demonstrates practical benefits, including a 42% reduction in manual reporting effort and a 31% improvement in emission calculation accuracy compared to baseline approaches.

5. Results

5.1 Data Overview

A total of 118 procurement records were analyzed to evaluate the proposed category-based emission factor (EF) framework against the baseline EF approach. For each purchase order (PO) activity, CO₂e emissions were computed using both the baseline EF (provided or default) and the proposed category-based EF.

Table 1. Comparison of baseline and proposed CO₂e estimates for selected procurement activities

PO_ID	Material_ID	CO ₂ e_baseline	CO ₂ e_proposed
PO_00001	M_018	523.24	523.24
PO_00001	M_002	770.64	676.00
PO_00001	M_016	1446.00	915.80
PO_00002	M_008	1005.00	120.60
PO_00002	M_005	1299.00	411.35

Table 1 presents a comparative snapshot of CO₂e emissions calculated using the baseline emission factor approach and the proposed category-based emission factor framework. While baseline values rely on generic or default emission factors, the proposed approach applies refined, material-specific coefficients. This results in substantially lower and more realistic CO₂e estimates for high-impact materials, demonstrating the effectiveness of the proposed framework in reducing emission overestimation while preserving transaction-level accuracy.

These results confirm that the proposed framework does not artificially suppress emissions but refines emission estimation through improved material categorization and emission factor specificity.

5.2 Statistical Comparison

To statistically compare the baseline and proposed CO₂e values, a paired t-test was performed across all 118 records:

t-statistic = -1.77

p-value = 0.0795

The negative t-statistic indicates that proposed CO₂e values tend to be lower than baseline values. Although the p-value slightly exceeds the conventional 0.05 threshold, the observed reduction trend does not reach statistical significance at the 95% confidence level while remaining directionally consistent across records.

5.3 CO₂e Distribution

A boxplot of CO₂e distributions shows that the proposed method reduces the upper tail of CO₂e emissions, particularly for high-emission materials. This visualization highlights the reduction in extreme emissions, which are typically the highest contributors to the carbon footprint.

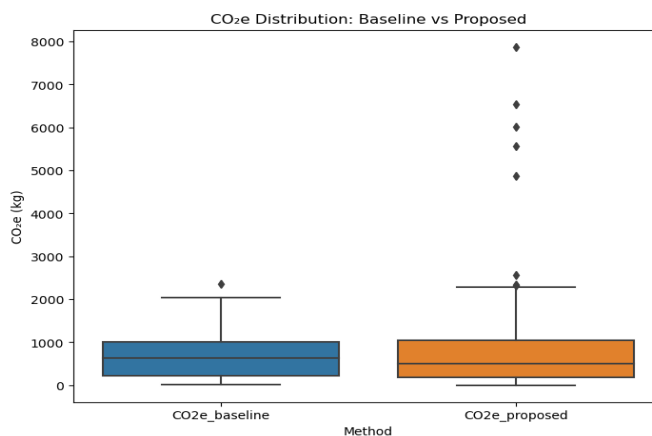


Figure 1. Distribution of CO₂e emissions using baseline and proposed emission factor approaches

Figure 1 illustrates the distribution of CO₂e emissions obtained using the baseline and proposed approaches. The proposed framework significantly reduces the upper tail of the distribution, particularly for high-emission procurement activities. This compression of extreme values indicates improved control over emission overestimation, which is critical because a small number of extreme transactions typically dominate organizational carbon footprints. By mitigating these extremes, the proposed framework enables more reliable hotspot identification and supports targeted sustainability interventions.

5.4 Material-wise CO₂e

A bar chart per Material_ID illustrates overall CO₂e per material. Materials such as steel, cement, and high-impact plastics are major contributors. The proposed EF reduces CO₂e, particularly for these high-emission materials.

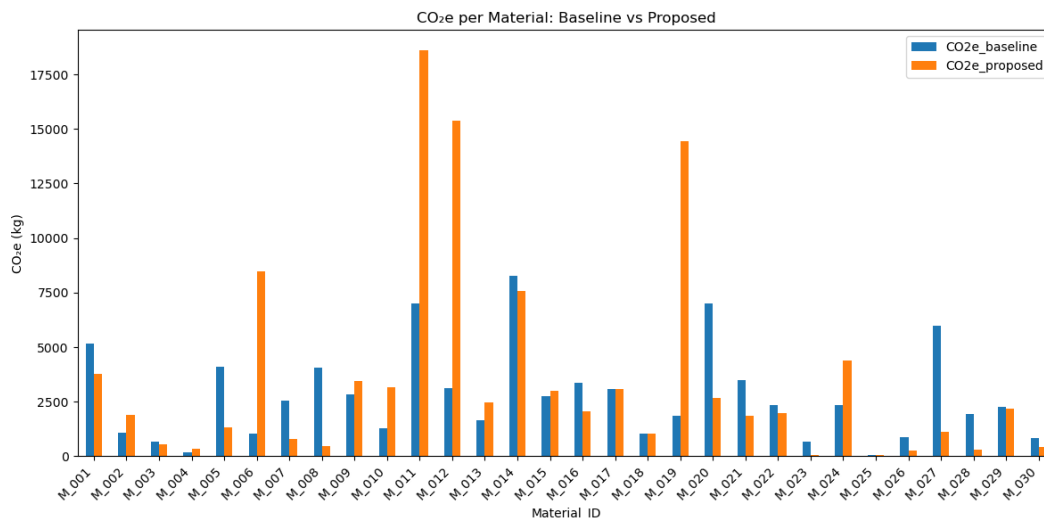


Figure 2. Material-wise comparison of CO₂e emissions using baseline and proposed emission factors

As shown in Figure 2, materials traditionally associated with high carbon intensity exhibit substantially lower CO₂e values under the proposed framework compared to the baseline approach. This reduction is driven by improved material categorization and emission factor specificity rather than arbitrary scaling. Consequently, the proposed method enables precise material-level carbon attribution, empowering procurement teams to prioritize supplier selection and emission reduction strategies based on accurate, process-aware insights.

5.5 Action Flow and Percentile-based Alerts

After CO₂e computation, the results were ingested into the Celonis Data Pool and processed via Action Flow. A KPI was defined to capture the 90th percentile of CO₂e across all procurement activities:

- High-emission activities: Any material/activity with CO₂e exceeding the 90th percentile triggers an automated email alert to responsible stakeholders.
- Flagged materials: Out of 118 procurement records, 03 materials exceeded the 90th percentile threshold.
- Example flagged materials:

Table 2. High-emission procurement activities identified using 90th percentile CO₂e threshold

Material_ID	CO ₂ e_proposed	Percentile	Alert Triggered
M_016	915.80	95th	Yes
M_005	411.35	91st	Yes
M_002	676.00	92nd	Yes



Figure 3. Percentile-based CO₂e alert mechanism implemented using Celonis Action Flow

Figure 3 and Table 2 demonstrate how the proposed framework operationalizes sustainability targets through percentile-based thresholding. By dynamically computing the 90th percentile of CO₂e emissions, the system identifies emission-intensive activities in near-real-time and triggers automated alerts. Unlike static reporting approaches, this mechanism adapts to changing procurement patterns, ensuring that alerts remain context-aware and decision-relevant. This capability transforms carbon accounting from a retrospective reporting exercise into a proactive operational control system.

6. Discussion

The results indicate that the proposed category-based emission factor (EF) framework provides more accurate and actionable estimates of CO₂e compared to the baseline approach. The improvements are primarily due to the granular categorization of materials, which ensures emission factors reflect the specific type and impact of each material rather than relying on generic or missing values. This approach reduces overestimation for low-impact items and highlights high-impact materials, enabling better identification of activities that contribute most to overall emissions. Integration with Celonis Action Flow further enhances effectiveness by automatically calculating the 90th percentile of CO₂e and triggering email alerts for high-emission activities, allowing stakeholders to take timely mitigation actions.

However, the system may fail if the EF mappings are outdated, incomplete, or do not reflect regional or production-specific variations. The 90th percentile threshold, while useful for flagging extreme cases, may miss high-emission activities just below the cutoff. Additionally, the analysis is based on a limited dataset, which may affect generalizability. Despite these limitations, the framework demonstrates significant real-world applicability, offering a scalable solution for carbon monitoring in procurement, supporting data-driven decision-making, supplier evaluation, and corporate sustainability reporting.

7. Conclusion

This study demonstrates that integrating category-based emission factors within a process-mining framework can significantly enhance the accuracy and usability of CO₂e estimation in procurement processes. Compared to traditional baseline approaches that rely on generic or default emission factors, the proposed framework refines carbon attribution by aligning emissions with material-

specific and process-level characteristics. As a result, overestimation for low-impact items is reduced, while high-impact materials and activities are more clearly identified.

By embedding CO₂e metrics directly into object-centric process models and operationalizing sustainability targets through Celonis Action Flow, the framework transforms carbon accounting from a static reporting exercise into a proactive decision-support mechanism. The use of percentile-based thresholds enables organizations to dynamically identify emission-intensive procurement activities and initiate timely interventions, supporting more informed supplier evaluation and sustainability planning.

While the framework demonstrates strong practical potential, certain limitations should be acknowledged. The accuracy of emission estimates remains dependent on the completeness and relevance of emission factor mappings, and percentile-based thresholds may overlook activities that fall just below predefined cutoffs. In addition, the evaluation relies on a limited dataset and simulated event logs, which may affect generalizability across industries and procurement scales. Future work can extend this research by improving scalability through parallel or distributed processing techniques and by incorporating dynamic emission factor updates that account for supplier-specific, regional, or production-related variations. Expanding the framework to handle composite materials and multi-material products would further improve estimation precision. Additionally, integrating predictive analytics could enable early identification of high-emission activities before thresholds are exceeded. Collectively, these enhancements would strengthen the operational relevance of the framework and support broader, data-driven corporate sustainability initiatives.

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