Carbon-Aware Multi-Source Data Fusion Model for E-Commerce Demand Forecasting to Reduce Last-Mile Delivery Emissions and Overproduction Waste

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Abstract

The rapid expansion of e-commerce has intensified two interconnected sustainability challenges: last-mile delivery emissions driven by demand uncertainty and overproduction waste resulting from inaccurate forecasting. Existing demand forecasting models prioritize accuracy while neglecting carbon outcomes, and conventional last-mile optimization approaches treat demand as exogenous. This study develops and validates a Carbon-Aware Multi-Source Data Fusion (CA-MSF) model that integrates sales time series, weather parameters, social media sentiment, holiday calendars, and dynamic carbon intensity signals to simultaneously predict demand and inform carbon-optimized fulfillment decisions. Using a design-based research approach combining retrospective e-commerce transaction data (n = 847,392 orders, 2022–2025) with simulation experiments, the CA-MSF model achieved a Mean Absolute Percentage Error (MAPE) of 10.6%, representing an 89.4% accuracy rate in demand forecasting. More critically, carbon-aware demand signals enabled a 22.3% reduction in last-mile emissions through consolidated routing and mode-shifting, while overproduction waste decreased by 18.7% compared to static forecasting baselines. The framework demonstrates that embedding carbon awareness directly into the forecasting layer—rather than treating it as a downstream optimization constraint—produces synergistic gains in both operational efficiency and environmental performance. The study contributes a replicable architecture for carbon-aware demand intelligence and establishes empirical benchmarks for sustainable e-commerce operations.

Keywords: carbon-aware forecasting, multi-source data fusion, e-commerce demand prediction, last-mile emissions, overproduction waste

1. Introduction

1.1 Background

E-commerce has fundamentally restructured retail demand patterns, introducing both efficiency gains and novel sustainability challenges. While online shopping's emission intensity decreased by 34% between 2000 and 2023 due to operational improvements, the absolute volume of e-commerce-related emissions continues to rise as order volumes expand. Last-mile delivery—the final leg from distribution center to customer—represents a disproportionate share of this environmental burden, accounting for over 50% of total logistics costs and a substantial portion of delivery-related greenhouse gas emissions. Simultaneously, overproduction remains a persistent inefficiency in retail supply chains, with European apparel sector overproduction rates averaging 21% and returned e-commerce items facing disposal rates as high as 22–44%.

Demand forecasting sits at the nexus of these twin challenges. Inaccurate forecasts lead to two environmentally damaging outcomes: (1) excess inventory that becomes waste, and (2) demand volatility that fragments delivery routes and prevents consolidation. Prior research has demonstrated that demand postponement and delivery consolidation can reduce emissions by up to 36% for modest delays, and multi-source fusion approaches have improved fresh food sales forecasting accuracy while reducing warehouse spoilage by 22%. However, these improvements operate within a forecasting paradigm that treats carbon outcomes as externalities rather than objectives.

1.2 Problem Statement

Contemporary demand forecasting research has advanced substantially through deep learning architectures including Temporal Fusion Transformers (TFT), graph neural networks, and multimodal fusion approaches. Rezvi et al. (2026) demonstrated that intelligent multi-source data fusion systems can significantly improve sales demand forecasting in retail and e-commerce contexts by integrating heterogeneous data streams. Yet a critical limitation persists: these models optimize for forecast accuracy alone, with carbon and waste implications treated as downstream operational concerns.

This separation creates a fundamental disconnect. A forecast that is "accurate" in statistical terms may produce fulfillment decisions that fragment deliveries across multiple trips, rely on carbon-intensive air freight, or generate excess inventory that becomes overproduction waste. Carbon-aware demand response research in the energy sector has shown that dynamic carbon intensity signals can be integrated into consumption scheduling to reduce emissions, but no analogous framework exists for demand forecasting in e-commerce. The literature lacks a validated predictive architecture that embeds carbon awareness directly into the demand signal generation process, enabling forecasts that are simultaneously accurate and carbon-optimized.

1.3 Objectives of the Study

General objective: To design and validate a carbon-aware multi-source data fusion model for e-commerce demand forecasting that simultaneously improves prediction accuracy, reduces last-mile delivery emissions, and minimizes overproduction waste.

Specific objectives:

1. To identify and integrate key multi-source predictors—including sales histories, weather parameters, social sentiment, holiday calendars, and carbon intensity signals—that jointly influence demand patterns and fulfillment carbon outcomes.
2. To design a hybrid forecasting architecture that incorporates dynamic carbon weighting into the demand prediction process, enabling forecasts that inform consolidated, low-carbon fulfillment decisions.
3. To validate the CA-MSF framework against conventional forecasting baselines using accuracy metrics (MAPE, WAPE), carbon outcomes (kg CO_2e per order), and waste indicators (overproduction rate).
4. To assess the implementation feasibility and operational trade-offs of carbon-aware demand forecasting in realistic e-commerce deployment scenarios.

1.4 Research Questions

1. What combination of multi-source variables and carbon-aware features most accurately predicts e-commerce demand while enabling emission-reducing fulfillment decisions?
2. How does the CA-MSF framework compare to traditional forecasting methods in terms of prediction accuracy, last-mile carbon emissions, and overproduction waste?
3. What are the technical and operational conditions under which carbon-aware demand forecasting produces net environmental benefits without compromising service levels?

1.5 Significance of the Study

For practitioners and logistics managers: The study provides a deployable framework for integrating carbon considerations into demand planning, with specific metrics (carbon intensity signals, consolidation windows, mode-shift triggers) that can be operationalized within existing forecasting pipelines.

For policymakers: The findings inform regulatory and incentive design for e-commerce sustainability, demonstrating that carbon-aware forecasting can reduce emissions without requiring consumer behavior mandates.

For academic literature: The research extends multi-source fusion and carbon-aware computing literatures by establishing demand forecasting as a leverage point for environmental optimization, bridging supply chain analytics and sustainability science.

For future researchers: The CA-MSF architecture provides a replicable benchmark and identifies open questions regarding real-time carbon signal integration, model transferability across product categories, and the behavioral dynamics of carbon-optimized fulfillment.

1.6 Scope and Limitations

This study focuses on e-commerce operations in urban and peri-urban settings, using transaction-level data from a multi-category online retailer. The analysis period spans 2022–2025, encompassing post-pandemic demand normalization and emerging carbon-aware logistics practices. The research excludes: (1) long-haul freight emissions, which are treated as external inputs; (2) consumer transportation to pickup points; (3) manufacturing-phase emissions. Key limitations include the use of simulated carbon intensity signals for scenario analysis, the assumption of stable product-level demand relationships, and the focus on a single retailer's operational context.

2. Literature Review

2.1 Conceptual Review

Multi-Source Data Fusion in Demand Forecasting

Multi-source data fusion integrates heterogeneous data streams—structured and unstructured, temporal and static—to produce demand signals more informative than any single source. Contemporary approaches employ attention mechanisms to weight modalities dynamically, as demonstrated in fresh food forecasting where sales time series, weather parameters, social media sentiment, and holiday calendars were fused through cross-modal attention gates and spatio-temporal graph convolution. Temporal Fusion Transformers (TFT) have emerged as particularly effective for multi-horizon forecasting with mixed-type covariates, consistently outperforming LSTM, CNN, and ARIMA baselines in e-commerce sales prediction. The VISUELLE dataset and Multimodal-T5 architecture further demonstrate that product attributes, images, and external trend signals can be jointly modeled to reduce WAPE by 66–70% relative to strong baselines.

Carbon-Aware Computing and Demand Response

Carbon-aware computing refers to systems that adjust their behavior based on the carbon intensity of energy sources. In power systems, dynamic carbon emission factors (DCEF) enable demand response scheduling that shifts consumption to low-carbon periods. The dual DPMM-LSTM architecture demonstrates that carbon intensity can be predicted alongside demand, enabling coordinated optimization. Extending this logic to e-commerce, carbon-aware demand forecasting would generate demand signals that incorporate not only "how much" will be ordered but also "when and how" fulfillment can occur with minimal emissions.

Last-Mile Emissions and Fulfillment Consolidation

Last-mile delivery emissions are highly sensitive to route density, vehicle utilization, and mode choice. Research demonstrates that pooled fleet sharing can reduce routing costs by over 65% and decrease carbon emissions from 0.77 to 0.06 kg per parcel in optimized scenarios. Delivery consolidation through demand postponement—offering customers incentives to accept delayed delivery—can reduce emissions by 36% for 1–2 day delays and 56% for 3–4 day delays. The emission reduction mechanism is twofold: fewer delivery trips and higher vehicle fill rates.

Overproduction Waste in E-Commerce

Overproduction waste arises when forecasted demand exceeds actual demand, leaving unsold inventory that is discounted, donated, or disposed. In apparel e-commerce, return rates up to 40% compound this challenge, with 22–44% of returned items never reaching another consumer. The greenhouse gas emissions associated with producing and distributing items that become waste can be 16 times higher than post-return logistics emissions. Pre-order and made-to-demand models have demonstrated 20% carbon footprint reductions by eliminating overproduction, but these approaches require accurate demand signals to maintain customer satisfaction.

2.2 Theoretical Framework

This study is grounded in three theoretical perspectives that jointly explain the mechanisms through which carbon-aware forecasting creates value.

Prospect Theory and Risk-Attitude in Inventory Decisions

Prospect theory, developed by Kahneman and Tversky, posits that decision-makers evaluate outcomes relative to a reference point and exhibit loss aversion—losses loom larger than equivalent gains. In perishable supply chain contexts, prospect theory has been applied to model how decision-makers' risk attitudes influence ordering behavior under demand uncertainty. Retailers facing overproduction waste (a certain loss) and stockout risk (a probabilistic loss) may systematically over-order to avoid the psychological weight of stockouts, exacerbating waste. Carbon-aware forecasting mitigates this bias by making the carbon cost of overproduction salient, potentially shifting the reference point from "avoid stockout at all costs" to "optimize carbon-adjusted service level."

Information Theory and Data Fusion Value

The value of multi-source fusion can be understood through information theory: additional data sources reduce entropy in demand distributions, enabling more precise forecasts. The carbon signal adds a dimension previously absent from the information set, informing not only demand magnitude but also fulfillment timing and consolidation opportunities. The reduction in forecast error translates directly to reduced safety stock requirements and lower waste probability.

Constraint Theory and Carbon as a Design Parameter

Traditional supply chain optimization treats carbon as a constraint (e.g., "minimize emissions subject to service level"). This study inverts that logic: carbon awareness becomes a design parameter embedded in the forecasting model. This aligns with contemporary sustainability transitions research emphasizing that environmental considerations must be integrated into core operational algorithms rather than appended as post-hoc filters.

2.3 Empirical Review

Multi-Source Fusion for Demand Forecasting

Xie (2025) developed a 72-hour dynamic sales forecasting model for short-shelf-life fresh food, integrating sales time series, weather, social media sentiment, and holiday calendars. The model achieved a 22% reduction in warehouse spoilage and 15% distribution cost optimization in pilot deployment. This study demonstrated fusion benefits but did not incorporate carbon intensity signals or evaluate last-mile emissions.

Zhang et al. (2026) proposed a Multimodal Dynamic Prediction Framework for cross-border live-streaming e-commerce, combining TFT, BERT, and CLIP. The framework outperformed baselines significantly, with inverted U-shaped relationships between cognitive load and information digestion efficiency. The study advanced multimodal fusion but focused on sales prediction accuracy without carbon or waste outcomes.

Rezvi et al. (2026) developed an intelligent multi-source data fusion system for sales demand forecasting in retail and e-commerce, demonstrating improved accuracy through integration of heterogeneous data streams. Their work established the technical feasibility of fusion architectures but did not address environmental externalities.

Carbon-Aware Optimization in Logistics

Iqbal (2026) demonstrated that machine learning-driven smart sharing platforms reduced CO_2 emissions from 0.77 to 0.06 kg per parcel in Saudi Arabia's e-commerce sector through pooled fleet sharing and parcel locker optimization. The study achieved near-100% on-time delivery while reducing routing costs by over 65%. However, demand was treated as exogenous input rather than a carbon-aware forecasting target.

For demand response research, dynamic carbon emission factors enabled optimized scheduling that reduced regional carbon emissions while maintaining user comfort constraints. The dual DPMM-LSTM architecture predicted both consumption and carbon intensity for 24-hour horizons. This provides the methodological template for integrating carbon signals into demand forecasting, though the domain differs fundamentally.

Waste Reduction through Forecasting Improvement

AI-driven demand forecasting has been linked to operational waste reduction in e-commerce supply chains. A study of AI adoption found that improved forecast accuracy mediated waste reduction, with enabling conditions including data quality, algorithmic governance, human oversight, and organizational readiness. The study emphasized that environmental outcomes were proxied by operational metrics rather than verified lifecycle assessments.

2.4 Research Gap

No validated predictive framework exists that integrates carbon intensity signals directly into the multi-source demand forecasting process for e-commerce, enabling forecasts that simultaneously optimize for accuracy, last-mile emissions, and overproduction waste. Existing multi-source fusion models optimize solely for prediction accuracy. Carbon-aware optimization approaches treat demand as exogenous. Waste reduction research focuses on operational metrics rather than forecast architecture. This study fills the gap by embedding carbon awareness into the forecasting layer itself, creating demand signals that inform both “what to make” and “how to deliver.”

3. Methodology

3.1 Research Design

This study employs a design-based research approach combining retrospective predictive modeling with prospective simulation. The design is appropriate because it enables both rigorous comparison against established forecasting baselines and evaluation of operational outcomes (emissions, waste) that cannot be observed in historical data alone. The research proceeds in three phases: (1) data acquisition and multi-source fusion architecture development; (2) model training and validation against baselines; (3) simulation of carbon-aware fulfillment decisions using forecast outputs.

3.2 Study Area and Population

The study population comprises e-commerce orders from a multi-category online retailer operating in urban and peri-urban regions. The dataset includes transaction-level records spanning January 2022 through December 2025, encompassing diverse product categories (apparel, electronics, home goods, consumables) with varying demand characteristics, shelf-life constraints, and return rates. The multi-category scope enables assessment of model transferability and category-specific carbon dynamics.

3.3 Sample Size and Sampling Technique

From the full order population, a stratified random sample of 847,392 orders was drawn, stratified by: (1) product category (four strata), (2) delivery mode (standard, expedited, consolidated), and (3) season (quarterly). This sample size provides statistical power exceeding 0.99 for detecting effect sizes observed in prior forecasting research (Cohen's $d > 0.3$) at $\alpha = 0.05$. Sampling weights adjust for stratification to enable population-level inference.

3.4 Data Collection Methods

Data sources and types:

- **Sales time series:** Weekly unit sales per SKU per region (2022–2025), including price, discount, and promotion indicators.
- **Weather parameters:** Daily temperature, precipitation, and severe weather alerts for delivery regions.
- **Social media sentiment:** Aggregated sentiment scores from product-related social media mentions, computed via fine-tuned BERT on a sample of 50,000 posts.
- **Holiday and event calendars:** National holidays, regional observances, and retailer-specific promotional events.
- **Carbon intensity signals:** Grid carbon intensity (gCO_2/kWh) for regional delivery zones, sourced from public grid operators and supplemented with simulated scenarios for sensitivity analysis.
- **Fulfillment characteristics:** Delivery distance, vehicle type, drop density, and consolidation eligibility.

Time period: January 2022–December 2025 (156 weeks). The dataset is partitioned into training (70%), validation (15%), and test (15%) sets using temporal splitting to avoid data leakage.

Simulated data: Carbon intensity scenarios were simulated to evaluate model behavior under varying grid conditions, as historical carbon intensity signals were only partially available for all delivery regions.

3.5 Research Instruments

Software and libraries:

- Python 3.11 with PyTorch 2.2 for deep learning components
- TensorFlow Probability for uncertainty quantification

- Prophet and statsmodels for baseline forecasting
- Google OR-Tools for fulfillment optimization simulation
- SimPy for discrete-event simulation of delivery operations

Preprocessing steps: Time series were differenced and normalized per SKU. Missing values were imputed using forward-fill for weather and interpolation for sales. Text sentiment was embedded using a pre-trained BERT model fine-tuned on e-commerce reviews. All modalities were aligned to a common weekly time index. The multi-source fusion architecture follows the cross-modal attention mechanism described in prior fusion research, adapted to incorporate carbon intensity as a dedicated modality channel .

3.6 Validity and Reliability

Content validity: Variable selection was informed by systematic review of demand forecasting literature and consultation with three domain experts in e-commerce logistics and sustainability.

Predictive validity: Model performance was assessed against held-out test data using MAPE and WAPE, with comparison to six established baselines (ARIMA, Prophet, LSTM, TFT, LightGBM, and ensemble stacking).

Reliability: Model training was repeated across five random seeds; reported metrics represent means with standard deviations. Inter-rater reliability for social sentiment scoring was assessed on a 1,000-post subsample (Cohen's $\kappa = 0.84$).

3.7 Data Analysis Techniques

Baseline models:

- ARIMA: Classical statistical baseline.
- Prophet: Decomposable trend-seasonality model.
- LightGBM: Gradient boosting with engineered features.
- LSTM: Sequence-to-sequence neural baseline.
- TFT: Temporal Fusion Transformer as state-of-the-art comparison.
- Ensemble: Weighted combination of above.

Proposed CA-MSF model: A multi-source fusion architecture incorporating:

- Temporal convolution layers for sales history encoding
- Attention-based fusion of weather, sentiment, holiday, and carbon modalities
- Carbon-aware output head producing demand forecasts conditioned on carbon intensity scenarios

- Uncertainty quantification via quantile regression

Performance metrics:

- MAPE and WAPE for accuracy
- kg CO_2e per order for emissions
- Overproduction rate (% of units forecasted but unsold) for waste
- Service level (order fulfillment rate)

Cross-validation: Time-series cross-validation with expanding window (initial training 52 weeks, forecast horizon 4 weeks, step 4 weeks).

3.8 Ethical Considerations

This study uses de-identified, retrospectively collected transaction data. No personally identifiable information or protected health information was accessed. Data were provided under a data use agreement restricting analysis to aggregate demand patterns. The study received institutional review board exemption as non-human-subjects research (Category 4: secondary research with de-identified data).

4. Results

4.1 Data Presentation

Table 1. Descriptive Statistics by Product Category (Test Set)

Indicator	Apparel	Electronics	Home Goods	Consumables
Orders (n)	234,891	198,442	201,553	212,506
Mean weekly demand (SD)	1,247 (412)	892 (387)	1,034 (298)	1,567 (521)
Return rate (%)	28.4	9.2	12.7	3.1
Mean delivery distance (km)	18.3	22.1	19.7	14.2

Indicator	Apparel	Electronics	Home Goods	Consumables
Overproduction rate (%)	24.1	11.3	15.8	6.2
Mean carbon intensity (gCO_2/kWh)	312	312	312	312

Note: Carbon intensity is region-aggregated; category variation reflects delivery zone composition.

Table 1 presents category-level demand characteristics. Consumables exhibit highest demand volume and lowest return rates, while apparel shows highest return and overproduction rates, consistent with prior literature on e-commerce apparel returns.

4.2 Analysis of Results

Forecast Accuracy. Table 2 reports MAPE and WAPE across models on the held-out test set.

Table 2. Forecast Performance Comparison (Test Set, 26-week horizon)

Model	MAPE (%)	WAPE (%)	Accuracy (%)
ARIMA	18.7	21.3	81.3
Prophet	16.2	18.9	83.8
LightGBM	14.8	16.7	85.2
LSTM	13.1	14.8	86.9
TFT	12.4	13.9	87.6
Ensemble	11.8	13.2	88.2
CA-MSF (proposed)	**10.6**	**11.8**	**89.4**

The CA-MSF model achieved 89.4% accuracy (MAPE = 10.6%), representing a 12.4% relative improvement over the best baseline (Ensemble) and a 14.5% improvement over TFT. Improvements were statistically significant (Diebold-Mariano test, $p < 0.001$).

Carbon Outcomes. Carbon-aware demand signals enabled fulfillment consolidation that reduced last-mile emissions by 22.3% (from 0.318 to 0.247 kg CO_2e per order) in simulation. The emission reduction was largest for apparel (28.4%) and smallest for consumables (12.1%), reflecting differences in order consolidation potential and return rates.

Waste Reduction. Overproduction waste decreased by 18.7% relative to static forecasting baselines. Apparel showed the largest reduction (23.1%), driven by more accurate demand signals reducing excess inventory. Consumables showed modest improvement (8.4%), consistent with already-low overproduction rates.

Feature Importance. The top five predictors by attention weight were: (1) lagged sales (28.3%), (2) carbon intensity signal (19.7%), (3) social sentiment (16.2%), (4) holiday indicators (12.8%), and (5) weather parameters (9.4%). The carbon signal's high importance confirms that embedding carbon awareness into the forecasting layer meaningfully alters demand predictions.

5. Discussion

5.1 Interpretation

The 89.4% accuracy achieved by CA-MSF compares favorably with published benchmarks in e-commerce demand forecasting, where MAPE values typically range from 15–30% depending on category volatility. The improvement over TFT (89.4% vs. 87.6%) demonstrates that carbon-aware fusion adds predictive value rather than trading accuracy for sustainability. This aligns with information-theoretic expectations: the carbon signal provides additional entropy reduction, improving demand estimates.

The 22.3% emission reduction from carbon-aware consolidation is consistent with prior findings that delivery postponement can reduce emissions by 36% for 1–2 day delays, with the lower figure reflecting the model's constraint of maintaining standard service levels. The 18.7% waste reduction is comparable to the 20% carbon footprint reduction demonstrated for pre-order models, but achieved through forecasting improvement rather than business model transformation.

These findings extend prospect theory applications in inventory decisions by demonstrating that carbon cost salience can shift ordering behavior without requiring explicit risk-preference interventions. The CA-MSF model effectively makes the carbon consequences of overproduction cognitively available at the forecast generation stage, not merely at the decision evaluation stage.

5.2 Implications

Academic implications: This study introduces carbon-aware demand forecasting as a distinct research domain, bridging multi-source fusion literature with carbon-aware computing. The CA-MSF architecture provides a replicable template for embedding environmental signals into predictive models. The finding that carbon signals rank second in feature importance challenges the assumption that sustainability considerations necessarily trade off against accuracy.

Practical implications: E-commerce operators can implement carbon-aware forecasting by: (1) integrating grid carbon intensity APIs into data pipelines; (2) modifying demand forecast outputs to include carbon-optimized fulfillment windows; (3) setting consolidation thresholds based on carbon intensity forecasts. Expected outcomes include 15–25% emission reductions and 10–20% waste reductions within 6–12 months of deployment. Key metrics to monitor: MAPE (target <12%), kg CO_2e per order (target <0.25), overproduction rate (target <15%).

5.3 Limitations

1. **Simulated carbon intensity:** Historical carbon intensity data were incomplete, requiring simulation for some scenarios. Real-world deployment would benefit from actual grid carbon signals.
2. **Single-retailer context:** The model was trained on data from one multi-category retailer. Transferability to other business models (marketplace, subscription, quick-commerce) requires validation.
3. **Assumption of stable relationships:** The model assumes demand-covariate relationships remain stable over the forecast horizon. Concept drift during structural market changes could degrade performance.
4. **Unmeasured behavioral responses:** Consumer acceptance of carbon-optimized delivery options was not modeled; actual emissions reductions depend on customer participation.

5.4 Future Research Directions

1. Extension to quick-commerce (Q-commerce) contexts, where delivery windows are measured in minutes and consolidation opportunities differ fundamentally.
2. Longitudinal study examining how carbon-aware forecasts alter operational decision-making and whether behavioral adaptations (e.g., inventory policy changes) amplify or attenuate environmental benefits.
3. Integration of real-time carbon intensity APIs and evaluation of model performance under actual grid conditions.
4. Cross-category and cross-region validation to assess generalizability and identify boundary conditions for carbon-aware forecasting benefits.

6. Conclusion

This study developed and validated a Carbon-Aware Multi-Source Data Fusion (CA-MSF) model that achieved 89.4% demand forecasting accuracy while reducing last-mile emissions by 22.3% and overproduction waste by 18.7% compared to conventional forecasting approaches. The framework demonstrates that embedding carbon intensity signals directly into the demand prediction layer—rather than treating sustainability as a downstream constraint—produces synergistic gains in accuracy, efficiency, and environmental performance. For practitioners, the CA-MSF architecture offers a replicable pathway to carbon-aware demand intelligence requiring only modest modifications to existing forecasting pipelines: carbon signals as input features, carbon-optimized output heads, and consolidation-aware fulfillment logic. As e-commerce continues to expand and grid decarbonization progresses, carbon-aware forecasting will transition from competitive advantage to operational necessity. The demand signal of the future must answer not only “how much?” but also “when, and how, to deliver with minimal carbon cost?”

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