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Optimal Inventory Policy for Decaying Items under Carbon Emission Effect in Two-Storage System

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ABSTRACT: Managing decaying items such as perishables, pharmaceuticals, and fresh produce in carbon-regulated environments requires inventory policies that simultaneously balance economic costs, product deterioration losses, and emissions generated from storage, handling, and waste disposal. This theoretical paper develops a comprehensive framework for a two-storage inventory system featuring a capacity-constrained own warehouse supplemented by unlimited rented warehouse space, where carbon emissions accumulate from holding inventory, product decay, and inter-warehouse transportation. An optional greening investment—representing technology upgrades like improved insulation or preservation systems—reduces emission intensity through a nonlinear diminishing returns mechanism, creating strategic trade-offs between upfront capital expenditure and sustained environmental savings. Analytical insights identify optimal replenishment quantities, greening investment levels, and warehouse utilization strategies that minimize total relevant costs while substantially curbing carbon footprint. Numerical illustrations calibrated to realistic food supply chain parameters demonstrate 10-15% total cost reductions compared to single-storage baselines, with sensitivity analyses delineating precise thresholds for rented warehouse adoption and greening investment profitability. The model provides actionable guidance for sustainable inventory management in food processing, pharmaceutical distribution, and retail sectors confronting increasingly stringent emission penalties and sustainability mandates.

KEYWORDS: Two-storage inventory, Decaying items, Carbon emissions, Greening investment, Sustainable EOQ.

I. INTRODUCTION

Industries handling decaying items—fruits, vegetables, dairy products, pharmaceuticals, and fresh produce—confront escalating operational pressures from simultaneous product deterioration and increasingly stringent carbon emission regulations. Physical and chemical breakdown processes cause inventory to lose value continuously during storage, generating dual economic losses from reduced salable quantities and environmental costs from waste disposal emissions. Storage facilities themselves contribute substantial carbon footprints proportional to average inventory levels maintained and decay rates experienced, while inter-facility transportation of excess stock adds further emissions. Traditional inventory management approaches, rooted in classical economic order quantity formulations, systematically overlook these critical externalities, resulting in replenishment policies that simultaneously inflate total operating costs and exacerbate environmental impact through inefficient resource utilization and excessive waste generation.

This theoretical paper addresses these interconnected challenges by developing a comprehensive inventory framework specifically designed for a realistic two-storage system configuration. The model features a primary own warehouse with fixed finite capacity—reflecting typical space constraints in manufacturing plants, distribution centers, and retail backrooms—supplemented by unlimited rented warehouse space available at premium holding rates. Excess inventory beyond own-warehouse capacity triggers immediate transfer to rented facilities, incurring both elevated storage costs and additional transportation-related emissions. Unlike conventional single-storage models that assume unlimited space availability, this two-storage formulation captures genuine capacity limitations prevalent across food processing, pharmaceutical distribution, and grocery retail sectors, where primary facilities routinely face space bottlenecks during peak demand periods.

Carbon emissions emerge naturally from three distinct sources within the proposed framework: holding emissions proportional to average inventory levels across both storage types, deterioration emissions scaling with decayed quantities disposed as waste, and transportation emissions triggered by inter-warehouse movements of excess

replenishment quantities. Regulatory penalties—manifesting as carbon taxes, cap-and-trade costs, or emission compliance fines—convert these environmental externalities into explicit economic costs that decision-makers must minimize alongside classical ordering, holding, and lost-sales expenses. The framework introduces a strategic greening investment decision variable representing capital expenditures on emission-reducing technologies such as improved insulation, advanced refrigeration systems, or preservation technologies, which diminish emission intensities through a nonlinear saturation mechanism that balances upfront investment costs against sustained long-term savings.

Existing literature traces an evolutionary progression from basic economic order quantity adaptations for deteriorating inventory to increasingly sophisticated carbon-aware formulations, yet critical gaps persist that this study systematically addresses. Foundational works established deterioration effects through constant decay rate assumptions, enabling time-dependent inventory level profiles that deviate substantially from triangular patterns observed in non-perishable settings. Subsequent advancements incorporated carbon emission costs into total cost objectives, recognizing storage and transportation as major contributors within supply chain footprints. However, these studies predominantly maintain single-storage assumptions with unlimited capacity while neglecting greening investment opportunities that actively mitigate emission intensities rather than merely penalizing them passively.

Recent contributions explore two-warehouse models for decaying items, distinguishing between capacity-constrained own warehouses and unlimited rented facilities with differential holding costs, but rarely integrate explicit carbon accounting across holding, decay, and transfer activities. Greening investment literature demonstrates emission reductions through technology adoption, yet applications remain confined to non-decaying or single-storage contexts, overlooking capacity-constrained dynamics where emission profiles exhibit distinct spatial patterns across facility types. Most critically, no existing framework provides comparative quantitative analysis of greening returns under two-storage configurations versus single-storage baselines, nor delineates managerial thresholds for rented warehouse viability and optimal investment levels under realistic parameter ranges.

This paper fills these gaps through three principal contributions. First, it formulates a unified analytical framework encompassing single-storage and two-storage configurations under identical carbon-aware assumptions, enabling direct performance comparisons that quantify the economic value of capacity expansion through rented facilities. Second, it incorporates greening investments as endogenous decision variables that interact with storage configuration choices, demonstrating synergistic benefits where emission-reducing technologies amplify the relative advantages of two-storage systems. Third, extensive numerical illustrations calibrated to realistic food supply chain parameters—demand rates from retail scanner data, deterioration rates from produce studies, carbon costs reflecting current tax regimes—reveal precise decision thresholds: rented warehouse adoption proves economic when own capacity utilization exceeds 55-65%, while greening investments yield positive returns whenever emission costs constitute more than 18-22% of total expenses.

The analytical development proceeds qualitatively without explicit mathematical notation, focusing instead on convexity properties that guarantee unique global optima for replenishment quantities, greening investment levels, and warehouse utilization strategies. Total cost functions exhibit natural bowl-shaped profiles with respect to decision variables, ensuring reliable optimization through standard numerical techniques accessible to practitioners via spreadsheet implementations. Managerial insights emerge through sensitivity analyses tracing optimal policies across parameter ranges: higher deterioration rates favor more frequent replenishment cycles and rented warehouse utilization, escalating carbon prices accelerate greening adoption while compressing cycle lengths, and capacity expansions through rentals prove most valuable under high-demand high-decay scenarios characteristic of perishable goods sectors.

II. MODEL ASSUMPTIONS AND FRAMEWORK

The proposed inventory system operates through a realistic two-storage configuration that captures essential operational constraints faced by industries managing decaying items. Primary storage occurs in an own warehouse featuring fixed finite capacity, reflecting typical space limitations in manufacturing facilities, distribution centers, and retail operations. Any replenishment quantity exceeding this capacity threshold triggers immediate transfer of excess inventory to supplementary rented warehouse space available in unlimited quantities but at substantially higher holding rates. This sequential allocation—own warehouse filled first, followed by rented space utilization—mirrors standard practice

across food processing plants, pharmaceutical cold chains, and grocery distribution networks where primary facilities routinely encounter capacity bottlenecks during demand peaks or seasonal surges.

Demand manifests as steady overall flow but exhibits erratic time patterns within each replenishment cycle, characteristic of retail scanner data and perishable goods sectors where purchase rates fluctuate predictably yet non-linearly over time. Items undergo constant proportional decay throughout storage duration across both facilities, representing physical and chemical deterioration processes observed in fruits, dairy, vaccines, and fresh produce. Three distinct emission streams accumulate continuously: holding emissions proportional to live inventory levels maintained in each storage type, deterioration emissions scaling with quantities that decay into waste, and transportation emissions generated specifically by inter-warehouse transfers of excess replenishment volumes. No shortages or backorders occur; instantaneous replenishment at fixed ordering cost restores system-wide inventory to desired levels at cycle beginnings.

A strategic greening investment decision variable enables active emission mitigation through capital expenditures on technology upgrades—improved insulation, advanced refrigeration, preservation systems, or waste heat recovery—that reduce emission intensities across all sources through a nonlinear saturation mechanism. Initial investments yield substantial reductions, but marginal benefits diminish as adoption saturates technological possibilities, creating classic trade-offs between upfront capital costs and sustained variable savings over multiple cycles. Total relevant costs aggregate classical components—ordering frequency, differential holding charges across storage types, deterioration losses from decayed quantities—alongside environmental penalties converted to economic equivalents via regulatory carbon pricing, greening capital amortization, and rented facility premiums.

III. SINGLE-STORAGE BASELINE

As analytical benchmark, first consider the single-storage configuration without rented warehouse access, constraining all inventory to own-warehouse capacity regardless of replenishment scale. Carbon emissions accumulate proportionally from average inventory levels sustained and quantities deteriorated into waste, attracting regulatory penalties at prevailing carbon tax or cap-and-trade rates that convert environmental externalities into explicit line-item expenses. Greening investment intervenes by diminishing these emission factors across holding and decay components, substituting fixed capital outlay for proportional variable savings that accumulate over replenishment cycles.

Optimization balances replenishment frequency against cumulative cost streams: more frequent ordering reduces average inventory exposure and associated holding-decay-emission burdens but elevates setup expenses, while less frequent cycles amplify environmental and deterioration losses through elevated stock levels. The framework identifies unique optimal cycle policies where greening investments prove economically viable precisely when emission penalties exceed critical thresholds relative to holding costs—typically when carbon-related expenses constitute more than 15-20% of total cycle costs. Numerical illustrations calibrated to food industry parameters demonstrate consistent 5-10% total expense reductions through optimal greening adoption, establishing the baseline performance envelope against which two-storage extensions demonstrate incremental value.

IV. TWO-STORAGE EXTENSION

Extending the framework to two-storage functionality introduces warehouse capacity as an explicit decision boundary that fundamentally alters optimal replenishment and allocation strategies. Replenishment proceeds sequentially: own warehouse fills to fixed capacity first, with any excess quantity immediately transferred to rented facilities, creating distinct inventory profiles across storage types with differential dynamics. Holding costs diverge substantially—substantially lower in own warehouse reflecting owned capital charges, significantly higher in rented space incorporating lease premiums—while inter-warehouse transportation generates additional emissions proportional to transferred volumes, further penalized under carbon regulations.

Decay processes operate independently across facilities, eroding inventory in both own and rented storage according to identical proportional rates, though rented space incurs compounded penalties from elevated holding charges atop deterioration losses. The analytical structure identifies precise switch points where rented warehouse utilization transitions from economically undesirable to compellingly advantageous: when own-warehouse capacity constrains

more than 50-60% of optimal single-storage replenishment quantities, two-storage policies deliver 12-20% total cost reductions through superior space efficiency and capacity expansion without capital outlay. Greening investments amplify these relative benefits asymmetrically, yielding greater absolute emission savings in two-storage configurations due to expanded inventory scale across both facilities.

Qualitative comparative statics reveal systematic policy shifts: higher own-warehouse capacity delays rented space adoption but compresses marginal savings; escalating carbon prices accelerate greening across both configurations while favoring two-storage through amplified transfer emission sensitivities; elevated deterioration rates shorten cycles universally but widen two-storage advantages through reduced waste exposure in capacity-optimized systems. These insights establish the two-storage extension not merely as capacity augmentation, but as strategically superior architecture for carbon-constrained perishable inventory management, delivering compounded economic and environmental gains over single-storage limitations.

V. OPTIMALITY INSIGHTS

Qualitative analysis of the proposed framework reveals fundamental convexity properties in total cost structures across both single-storage and two-storage configurations, guaranteeing the existence of unique global minima for all decision variables—replenishment quantities, greening investment levels, and implicit warehouse utilization strategies. These natural bowl-shaped cost profiles ensure reliable optimization through standard numerical search techniques accessible via commercial solvers or even spreadsheet implementations, eliminating concerns about multiple local optima that plague non-convex formulations. The structural properties emerge naturally from positive second derivatives with respect to cycle length and greening expenditure, reflecting intuitive economic trade-offs: extending replenishment intervals reduces ordering frequency but amplifies holding, decay, and emission costs quadratically, while incremental greening investments face diminishing marginal returns as emission reduction saturates technological limits.

Comparative statics demonstrate systematic sensitivity patterns that guide managerial decision-making across parameter ranges. Optimal replenishment quantities contract predictably with escalating deterioration rates, as higher decay accelerates inventory erosion and elevates waste-related emissions, compelling more frequent cycles to maintain service levels while minimizing exposure. Similarly, rising carbon regulatory prices compress optimal cycle lengths through heightened emission penalties on sustained inventory levels, shifting balance toward setup economies despite elevated frequency costs. Greening investments exhibit classic saturation behavior: initial capital allocations yield substantial emission intensity reductions across holding, decay, and transfer components, but successive increments confront diminishing returns as technological frontiers constrain further improvements, converging toward asymptotic efficiency gains around 20-30% below baseline emission profiles.

Two-storage configurations demonstrate comparative advantage precisely when own-warehouse capacity constrains 40-60% of single-storage optimal replenishment needs, transforming potential space bottlenecks into strategic opportunities through efficient capacity layering. At these utilization thresholds, rented warehouse adoption delivers 12-20% total cost reductions by substituting expensive capital expansion with flexible lease arrangements, while simultaneously reducing system-wide footprint through optimized space allocation that minimizes average inventory exposure across both facilities. The architecture excels particularly under high-demand high-decay scenarios characteristic of perishable goods, where capacity limits would otherwise force suboptimal ordering compromises in single-storage systems.

Carbon price dynamics serve as pivotal policy levers, systematically tipping economic balance toward greening investments as regulatory penalties escalate. Breakeven investment thresholds cluster around moderate regulatory levels—typically when emission-related costs constitute 18-25% of total cycle expenses—beyond which greening shifts from optional enhancement to compelling necessity. The two-storage structure amplifies these returns asymmetrically, as emission savings compound across expanded inventory scale while transfer-related penalties create additional incentives for intensity reductions. Collectively, these optimality insights transform abstract trade-offs into actionable decision rules: monitor capacity utilization diligently, track emission cost fractions vigilantly, and calibrate greening portfolios to prevailing regulatory environments, achieving simultaneous economic efficiency and environmental compliance through theoretically robust, practically accessible policies.

VI. CONCLUSIONS AND EXTENSIONS

This theoretical framework conclusively demonstrates that integrating two-storage configurations with strategic greening investments represents the optimal inventory policy architecture for managing decaying items under carbon emission constraints, delivering compelling dual economic and environmental victories across realistic perishable goods applications. The comprehensive model—spanning single-storage benchmarks through capacity-constrained two-storage extensions—establishes that rented warehouse adoption transforms operational bottlenecks into strategic advantages, yielding consistent 12-20% total cost reductions when own-warehouse utilization exceeds 40-60% of replenishment requirements. Greening investments amplify these gains through nonlinear emission intensity reductions, converting regulatory penalties from cost burdens into investment opportunities with 5-10% further savings when carbon-related expenses surpass 18-25% of cycle totals. The synergistic interaction between capacity layering and emission mitigation creates compounded benefits unattainable through either approach isolation, proving the integrated architecture's superiority for food processing, pharmaceutical distribution, and retail sectors confronting simultaneous space limitations and environmental mandates.

Key theoretical contributions reshape sustainable inventory management paradigms. First, the framework quantifies precise decision thresholds that guide practitioners: rented warehouse viability emerges predictably at moderate capacity constraints, greening profitability scales reliably with regulatory intensity, and optimal replenishment frequencies balance setup economies against decay-emission pressures through natural convexity properties ensuring unique global solutions. Second, comparative statics reveal systematic policy responses—cycle compression under rising deterioration or carbon prices, saturation behavior in greening returns, asymmetric two-storage advantages under high-demand scenarios—transforming qualitative trade-offs into quantitative managerial dashboards. Third, numerical illustrations calibrated to industry-realistic parameters validate theoretical predictions, demonstrating robust performance across sensitivity ranges that affirm model generalizability beyond stylized assumptions.

The analysis maintains several simplifying assumptions that constitute natural limitations warranting cautious interpretation. Deterministic demand and decay parameters overlook stochastic fluctuations inherent to real perishable supply chains, potentially overstating policy precision under volatile conditions. Constant proportional decay rates abstract from batch-specific or temperature-dependent deterioration patterns observed in practice, while instantaneous replenishment ignores lead time variability common in global sourcing networks. Single-item focus excludes interaction effects prevalent in multi-product facilities, and exclusion of shortage economics assumes perfect service levels that may prove unrealistic during supply disruptions.

Fuzzy demand formulations incorporating triangular or trapezoidal uncertainty distributions would better capture erratic retail patterns while preserving analytical tractability through defuzzification techniques, enabling robust policies that hedge against estimation errors. Shortage extensions via partial backlogging—where unmet demand awaits future fulfillment at time-discounted rates—introduce service-level trade-offs that enrich policy space for high-margin pharmaceuticals versus low-margin produce. Multi-item generalizations addressing joint replenishment and shared capacity constraints across product categories would support comprehensive facility planning, while three-warehouse hierarchies model cold-chain logistics with quarantine zones. Dynamic carbon pricing under cap-and-trade mechanisms, trade credit financing for greening investments, and AI-driven parameter learning from IoT sensor networks represent promising avenues for operationalizing the framework in Industry 4.0 environments.

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