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Multiscale Thermodynamic Modeling and Energy Efficiency Optimization in Urban Logistics Systems

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ABSTRACT

Urban logistics systems, as critical infrastructures underpinning urban operations, have been increasingly constrained by rapid growth in energy consumption and persistent bottlenecks in energy efficiency improvement for green urban development. Existing studies have predominantly focused on route planning and scheduling optimization, while the thermodynamic nature of energy dissipation within logistics systems has been largely overlooked. As a result, dissipation mechanisms remain unclear, and cross-scale synergistic optimization has not been effectively realized, limiting fundamental improvements in energy efficiency. To address these limitations, a multiscale thermodynamic modeling and optimization framework for urban logistics operations was developed based on the principles of nonequilibrium thermodynamics. A three-layer nested bidirectional coupling modeling approach was proposed, in which microscopic powertrain irreversibility, mesoscopic traffic flow dissipation within road networks, and macroscopic topological disorder of logistics networks were integrated into a unified thermodynamic analysis framework. On this basis, a cross-scale entropy generation coordination mechanism was established, with entropy generation minimization adopted as the core optimization objective to achieve fundamental thermodynamic improvements in energy efficiency. The proposed framework and optimization mechanism were systematically validated through multi-scenario simulations and real-vehicle experiments, demonstrating high accuracy and effectiveness. This study provides a first-principles thermodynamic foundation for energy efficiency optimization in urban logistics systems, extends the application of nonequilibrium thermodynamics to complex engineering systems, and fills a critical research gap in multiscale coupled thermodynamic modeling within the logistics domain. A novel theoretical and technological pathway is thus offered for promoting low-carbon and sustainable urban logistics development.

1. INTRODUCTION

Urban logistics systems constitute a fundamental infrastructure supporting urban economic operations [1, 2]. The rapid escalation of energy consumption has not only intensified the imbalance between energy supply and demand but has also imposed significant environmental pressures, thereby rendering the transition toward green and energy-efficient logistics a global imperative [3, 4]. Current research on energy efficiency optimization in urban logistics has predominantly focused on geometric and temporal optimization of routing and vehicle scheduling [5-7], while the inherently thermodynamic and irreversible nature of energy consumption has been largely neglected. Consequently, an insufficient understanding of energy dissipation mechanisms within logistics systems has persisted. Urban logistics systems can be characterized as open nonequilibrium thermodynamic systems [8, 9], in which energy dissipation occurs across three scales: microscopic vehicle powertrain conversion, mesoscopic traffic flow dissipation within road networks, and macroscopic spatial heterogeneity in logistics networks. These processes are coupled through an energy degradation chain [10, 11]. However, the underlying cross-scale coupling mechanisms have not been explicitly characterized in existing studies, and a unified global optimization framework grounded in thermodynamic first principles remains absent [12]. As a result, improvements in energy efficiency have reached a bottleneck. From this perspective, elucidating energy degradation mechanisms through a thermodynamic lens and establishing a multiscale thermodynamic modeling and optimization framework are not only essential for advancing sustainable urban development but also aligned with the core emphasis of thermodynamics-oriented journals on innovative physical mechanisms.

Current studies on energy efficiency optimization in urban logistics are predominantly conducted within single-scale frameworks. At the microscopic scale, finite-time thermodynamics has been widely employed to characterize entropy generation associated with vehicle powertrain losses under transient operating conditions, thereby enabling optimization of powertrain control strategies [13, 14]. At the mesoscopic scale, approaches inspired by traffic flow fluid dynamics have been adopted; some studies have introduced entropy generation theory to describe congestion mechanisms, yet the relationship between congestion and energy consumption has not been quantitatively established [15, 16]. At the macroscopic scale, graph-theoretic approaches have been adopted to optimize logistics network topology and distribution routes, primarily focusing on minimizing travel distance or time while neglecting the influence of network structural properties on energy consumption [17, 18]. Significant gaps remain in existing multiscale studies. First, most approaches rely on sequential or unidirectional coupling strategies [19], without accounting for feedback effects from microscopic optimization to mesoscopic and macroscopic levels, thereby failing to capture the interactions among entropy generation processes across scales. Second, a unified thermodynamic metric has not been established [20], and exergy analysis and entropy generation minimization have not been consistently integrated throughout the modeling framework, making it difficult to quantify the contributions of irreversible losses at different scales. Third, optimization objectives have largely been limited to minimizing distance or time [21], rather than adopting global entropy generation minimization as the central criterion, and dynamic regulation mechanisms based on thermodynamic state awareness remain underdeveloped. Fourth, the topological disorder of logistics networks has not been incorporated into thermodynamic analysis, and the constraining role of structural entropy on overall energy consumption has been overlooked. These limitations collectively define a clear entry point for methodological innovation.

The objective of this study is to establish a multiscale thermodynamic modeling framework for urban logistics systems, through which cross-scale entropy generation coupling mechanisms can be elucidated, and a coordinated optimization and regulation strategy based on thermodynamic state awareness can be developed to achieve fundamental improvements in global energy efficiency. The primary contributions are reflected in three aspects. From a theoretical perspective, urban logistics systems are reformulated as open nonequilibrium thermodynamic systems, and a unified thermodynamic analysis paradigm integrating structure, operation, and energy consumption is established, thereby overcoming the limitations of conventional optimization approaches that emphasize geometric factors while neglecting underlying physical mechanisms. Furthermore, a three-dimensional characterization system comprising structural entropy, operational entropy, and congestion-induced entropy is proposed, enabling unified thermodynamic quantification across multiple scales. From a technical perspective, a three-layer nested bidirectional coupling modeling method is developed to ensure consistency among models at different scales. In addition, a coordinated regulation mechanism based on entropy generation decoupling and virtual exergy pricing is introduced, enabling closed-loop coordination between the physical layer and the control layer. From a methodological perspective, a dual-level iterative framework is constructed, integrating microscopic variational optimization, mesoscopic state mapping, and macroscopic global optimization. Within this framework, entropy generation minimization is consistently adopted as the core optimization principle throughout the entire process.

The overall structure of the study is organized in a logically progressive manner to form a coherent research framework. First, multiscale thermodynamic models and cross-scale bidirectional coupling mechanisms are established. Subsequently, a coordinated optimization framework and corresponding regulation strategies are developed. These are then validated through simulations and real-vehicle experiments to demonstrate their effectiveness. Finally, conclusions are drawn, limitations are analyzed, and future research directions are outlined. The technical route is constructed based on thermodynamic first principles and follows a closed-loop logical structure. Specifically, the research problem and innovation direction are first defined, followed by a systematic review of theoretical foundations and existing studies. Multiscale thermodynamic models at the microscopic, mesoscopic, and macroscopic levels, along with their coupling mechanisms, are then developed. A dual-level iterative optimization framework and coordinated regulation strategy are subsequently designed to achieve global entropy generation minimization. The effectiveness of the proposed approach is verified through multi-scenario simulations and real-vehicle experiments, leading to conclusions and future perspectives. Particular emphasis is placed on the multiscale coupling characteristics and the thermodynamic essence.

2. MULTISCALE THERMODYNAMIC MODELING OF URBAN LOGISTICS SYSTEMS

2.1 Three-layer nested bidirectional coupling paradigm

Existing energy consumption modeling approaches for urban logistics systems have largely been constrained to single-scale analyses or sequential unidirectional coupling frameworks. As a result, the interactions among entropy generation processes across different scales have not been adequately captured, leading to a disconnect between model representations and the intrinsic thermodynamic behavior of real-world systems. To address these limitations, a three-layer nested bidirectional coupling thermodynamic modeling framework is developed, integrating the microscopic, mesoscopic, and macroscopic scales within a unified analytical structure. Within this framework, exergy analysis is adopted as the consistent metric across all scales, while entropy generation minimization is employed as the global optimization criterion. This formulation enables precise cross-scale characterization of energy dissipation mechanisms in urban logistics systems. The overall framework is illustrated in Figure 1. The core innovation of this framework lies in the abandonment of conventional unidirectional modeling paradigms and the establishment of a bidirectional feedback structure across scales. Through this approach, the coupling relationships among microscopic powertrain entropy generation, mesoscopic traffic flow dissipation, and macroscopic network disorder are fundamentally revealed. This thermodynamically consistent modeling foundation provides a basis for subsequent cross-scale coordinated optimization.

The bidirectional nature of the coupling logic constitutes the core technical innovation of the proposed framework and is specifically manifested through the organic integration of forward driving and backward feedback mechanisms. The forward-driving mechanism is characterized by the determination of vehicle route allocation through the macroscopic logistics network topology, which subsequently modulates the traffic flow state at the mesoscopic level and ultimately influences the operating conditions and entropy generation characteristics of vehicle powertrains at the microscopic scale. Conversely, the backward feedback mechanism operates through the optimization of microscopic driving behavior, whereby velocity fluctuations are reduced, leading to enhanced stability of mesoscopic traffic flow and a reduction in congestion-induced entropy generation. This process further optimizes the spatial distribution of exergy dissipation at the macroscopic network level, thereby forming a closed-loop coupling structure. To resolve thermodynamic inconsistencies arising during the coupling of models across different scales, a multiscale thermodynamic consistency criterion is established. A distance-normalized entropy generation coefficient is introduced as the core variable for transmitting information from the mesoscopic scale to the microscopic scale, expressed as:

$$\eta_{road} = \int_0^L \dot{S}_{meso}(x)dx/L \tag{1}$$

where, $\dot{S}_{meso}(x)$ denotes the instantaneous entropy generation rate at position x along a road segment at the mesoscopic scale, and L represents the length of the road segment. This coefficient quantifies the modulation intensity of mesoscopic traffic flow dissipation on microscopic vehicle energy consumption. In addition, the generalized exergy cost is defined as the core feedback variable from the microscopic scale to the macroscopic scale, expressed as:

$$C_{ex} = \int_0^T \dot{E}_{micro}(t)dt + \lambda \cdot \eta_{road} \tag{2}$$

where, $\dot{E}_{micro}(t)$ represents the instantaneous exergy loss rate of the vehicle at the microscopic scale, T denotes the travel time over the road segment, and λ is the congestion entropy penalty coefficient. Through this formulation, microscopic exergy losses and mesoscopic congestion-induced dissipation are jointly quantified, thereby ensuring seamless coupling of models across all scales.

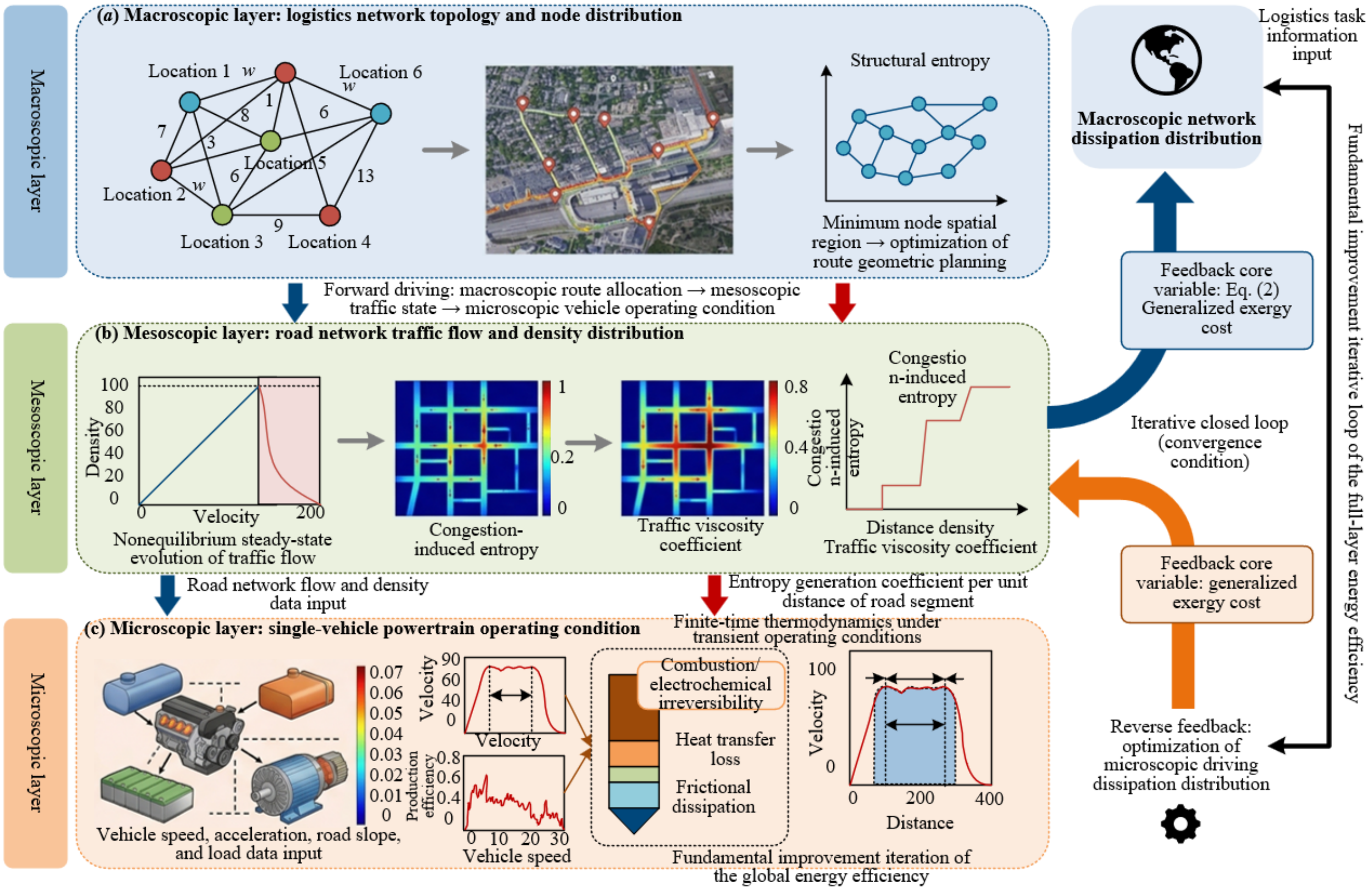


Figure 1. Three-layer nested bidirectional coupling thermodynamic modeling framework for urban logistics systems

The model architecture is designed around the coupling logic and thermodynamic consistency criteria, in which the input–output variables and dynamic iterative mechanisms of each scale are explicitly defined, forming a hierarchically structured and tightly integrated modeling system. At the microscopic scale, vehicle speed, acceleration, road gradient, and load are taken as input variables, while the instantaneous exergy loss rate $\dot{E}_{micro}(t)$ and cumulative entropy generation are produced as outputs. At the mesoscopic scale, road network flow and density serve as inputs, and congestion-induced entropy along with the distance-normalized entropy generation coefficient η_{road} are obtained as outputs. At the macroscopic scale, logistics network topology parameters and distribution task information are used as inputs, while global exergy balance results and structural entropy are generated as outputs. Dynamic iteration across the three scales is achieved through the exchange of coupling variables. Specifically, the route allocation results generated by the macroscopic model are transmitted to the mesoscopic model, where the coefficient η_{road} is computed and subsequently provided as input to the microscopic model. The microscopic model then outputs $\dot{E}_{micro}(t)$, which is used to update the generalized exergy cost C_{ex}. This cost is fed back to the macroscopic model to adjust network scheduling strategies. The process continues until entropy generation across all scales converges toward a stable state, thereby enabling an accurate characterization of the thermodynamic state of the entire system. The innovation of this architectural design lies in the explicit definition of variable transmission pathways and iterative mechanisms, through which the three layers are integrated into a unified system. This approach overcomes the limitations of conventional multiscale models that are treated as independent, ensuring both thermodynamic consistency and modeling accuracy.

2.2 Improved finite-time thermodynamic model under transient operating conditions

Conventional microscopic vehicle energy consumption models are primarily based on steady-state efficiency maps and are therefore unable to adequately represent transient operating conditions characterized by frequent acceleration, deceleration, idling, and braking in urban logistics. As a result, the irreversible entropy generation mechanisms within the powertrain cannot be accurately captured, leading to significant deviations in energy consumption prediction. To address these limitations, an improved model under transient operating conditions is developed based on finite-time thermodynamics. The core innovations are centered on the dynamic quantification of multi-source entropy generation, the thermodynamic integration of time constraints, the deep coupling between dynamics and thermodynamics, and the development of efficient solution methods. Through this framework, accurate prediction of microscopic energy consumption and entropy generation is achieved, thereby overcoming the limitations of conventional models in both accuracy and applicability. For entropy generation rate modeling, a differential formulation of the instantaneous entropy generation rate is introduced, in which multiple sources of irreversible losses within the powertrain are integrated. The conventional steady-state assumption is abandoned, and a dynamic relationship between entropy generation rate, vehicle speed, and acceleration variation is established. The governing equation is expressed as:

$$\dot{S}_{micro}=\dot{S}_{\mathrm{chem}}+\dot{S}_{\mathrm{heat}}+\dot{S}_{fric} \tag{3}$$

where, $\dot{S}_{micro}$ denotes the instantaneous entropy generation rate at the microscopic scale, $\dot{S}_{\mathrm{chem}}$ represents the entropy generation rate due to combustion or electrochemical irreversibility, $\dot{S}_{\mathrm{heat}}$ corresponds to the entropy generation rate due to heat transfer irreversibility, and $\dot{S}_{fric}$ denotes the entropy generation rate associated with frictional dissipation. By incorporating acceleration-related terms into the formulation, the dynamic variation of entropy generation in vehicle power systems under transient conditions can be accurately captured. For instance, the coupling between combustion irreversibility within internal combustion engines and variations in rotational speed and torque can be represented, as well as entropy increments associated with polarization losses in electric motors. This formulation resolves a critical limitation of conventional models in quantifying transient losses. For thermodynamic quantification under time constraints, a coupling model between delivery time windows and time-related exergy is proposed. The relaxation of the time window is defined as a generalized potential, and the exergy loss associated with time delay is derived as:

$$E_{time}=E_{ref}\left(1-\exp\left(-k\Delta t\right)\right) \tag{4}$$

where, E_{time} denotes the time-related exergy loss, E_{ref} represents the reference exergy associated with time, k is the time sensitivity coefficient, and Δt denotes the duration of the delay. Through this formulation, time constraints and energy dissipation are unified within a thermodynamic framework, addressing the gap in conventional models that neglect the thermodynamic implications of temporal factors.

To achieve precise coupling between vehicle dynamic characteristics and entropy generation mechanisms, a longitudinal vehicle dynamics–thermodynamics coupled equation is established. Key influencing factors, including road gradient and vehicle load, are incorporated into the entropy generation calculation, thereby overcoming the limitation of conventional models that consider only vehicle speed as a single variable. The coupled equation is expressed as:

$$m\ddot{x}+f_r mg\cos\theta+\frac{1}{2}\rho C_d A\dot{x}^2+mg\sin\theta=F_d-F_b \tag{5}$$

where, m denotes the total vehicle mass, $\dot{x}$ represents vehicle speed, $\ddot{x}$ denotes acceleration, f_r is the rolling resistance coefficient, θ is the road gradient, ρ is the air density, C_d is the aerodynamic drag coefficient, A is the frontal area, F_d is the driving force, and F_b is the braking force. This equation is deeply coupled with the instantaneous entropy generation rate equation, enabling real-time linkage between dynamic variables, such as vehicle speed and acceleration, and entropy generation. Consequently, the effects of road gradient and load variations on microscopic entropy generation can be accurately characterized. For the model solution, the determination of the minimum-entropy-generation velocity trajectory under transient operating conditions is innovatively reformulated as a two-point boundary value problem. The travel time and distance are imposed as constraints, while cumulative entropy generation is minimized as the objective function. The problem is solved numerically using the Pontryagin minimum principle, and the Hamiltonian is constructed as:

$$H=\dot{S}_{micro}+\lambda_1\dot{x}+\lambda_2\ddot{x} \tag{6}$$

where, λ_1 and λ_2 are costate variables. By solving the corresponding costate equations and boundary conditions, the optimal velocity trajectory can be obtained. This solution method overcomes the efficiency limitations of conventional numerical iterative approaches, while simultaneously ensuring solution accuracy and real-time applicability. It is therefore well suited for dynamic scheduling scenarios in urban logistics, where real-time optimization of driving strategies is required. As a result, the engineering applicability and predictive accuracy of the model are significantly enhanced, providing high-fidelity microscopic entropy generation data to support subsequent cross-scale coupling.

2.3 Congestion-induced entropy model under nonequilibrium steady-state traffic flow

Conventional mesoscopic traffic flow models have primarily focused on macroscopic relationships among flow, density, and velocity, while the energy dissipation mechanisms associated with congestion have not been quantified from a thermodynamic perspective. As a result, the amplification effect of congestion on microscopic vehicle entropy generation has not been revealed, and the coupling between mesoscopic and microscopic scales lacks a thermodynamic foundation. To address these limitations, the urban road network is treated as a continuous thermodynamic medium. By integrating concepts from nonequilibrium statistical mechanics and traffic flow hydrodynamics, a congestion-induced entropy model under nonequilibrium steady-state conditions is developed. The core innovations are centered on the quantitative definition of congestion-induced entropy, the characterization of nonequilibrium phase transition mechanisms, the establishment of cross-scale coupling relationships, and the adaptation to real-world data. Through this framework, precise linkage between mesoscopic traffic flow dissipation and microscopic entropy generation is achieved, thereby filling the gap in thermodynamic modeling at the mesoscopic scale. For the quantitative definition of congestion-induced entropy, a congestion entropy metric is introduced, defined as the integral of the additional entropy generation rate arising from velocity dispersion, vehicle interactions, and traffic signal interruptions. This formulation overcomes the limitations of conventional entropy models that consider only single contributing factors. The expression is given as:

$$S_{cong}=\int_0^T\int_0^L \dot{S}_{\mathrm{extra}}(x,t)dxdt \tag{7}$$

where, S_{cong} denotes congestion-induced entropy; $\dot{S}_{\mathrm{extra}}(x,t)$ represents the additional entropy generation rate at position x and time t; T is the observation period; and L is the length of the road segment. Based on the threshold characteristics of traffic flow density, a piecewise functional relationship between congestion-induced entropy and traffic density is established:

$$S_{cong}=\begin{cases}k_1\rho^2 & \rho<\rho_c\\ k_2\exp(\rho-\rho_c) & \rho\geq\rho_c\end{cases} \tag{8}$$

where, ρ denotes traffic density, ρ_c represents the critical density, and k_1 and k_2 are fitting coefficients. This formulation accurately captures the abrupt increase in the entropy generation rate before and after the onset of congestion and quantitatively characterizes the amplification effect of congestion on microscopic entropy generation.

To further reveal the thermodynamic nature of congestion, a nonequilibrium steady-state modeling approach is introduced. Drawing on the analogy with the Navier–Stokes equations in fluid dynamics, a traffic viscosity coefficient μ is incorporated to represent internal friction effects induced by driving behavior fluctuations and lane-changing interactions. This formulation overcomes the limitation of traditional traffic flow models that neglect microscopic behavioral disturbances. The entropy balance equation for traffic flow is derived as:

$$\frac{\partial S}{\partial t}+\nabla\cdot(Sv)=\dot{S}_{prod}+\dot{S}_{cong} \tag{9}$$

where, S denotes the entropy density of traffic flow, v represents the vehicle velocity vector, $\dot{S}_{prod}$ is the baseline entropy generation rate, and $\dot{S}_{cong}$ corresponds to the additional entropy generation rate induced by congestion. Within this formulation, congestion is interpreted as a nonequilibrium steady-state phase transition. When traffic density exceeds the critical density ρ_c, the system transitions from a free-flow state to a congested state. During this transition, the traffic viscosity coefficient μ increases sharply, resulting in a stepwise rise in the congestion-induced entropy generation rate $\dot{S}_{cong}$. This interpretation reveals the intrinsic mechanism underlying the onset and intensification of congestion from a thermodynamic perspective. To enable coupling between the mesoscopic scale and both the microscopic and macroscopic scales, the Onsager reciprocal relations are employed to establish a coupling equation between generalized thermodynamic forces and fluxes in traffic flow:

$$\dot{S}_{cong}=L_{ij}X_iX_j \tag{10}$$

where, L_{ij} denotes the Onsager coefficients, X_i represents the generalized force (i.e., the gradient of congestion-induced entropy), and X_j denotes the generalized flux (i.e., vehicle velocity). This formulation quantitatively characterizes the constraining effect of congestion entropy gradients on vehicle motion and enables the transformation of congestion-induced entropy into the distance-normalized entropy generation coefficient. This coefficient serves as the core variable transmitted from the mesoscopic scale to the microscopic scale, thereby providing a thermodynamically consistent linkage for cross-scale coupling. The relationship between nonequilibrium steady-state phase transitions in traffic flow and the evolution of congestion-induced entropy is illustrated in Figure 2. For practical implementation, a data adaptation strategy is developed. A mapping method is designed to relate congestion-induced entropy to floating vehicle data and road network simulation data. Specifically, parameters such as vehicle speed dispersion and interaction frequency are extracted from floating vehicle trajectory data and substituted into the congestion entropy formulation to enable real-time computation. Meanwhile, traffic flow density and velocity obtained from simulation data are transformed into road segment entropy generation coefficients, thereby achieving accurate integration between the mesoscopic model and real-world road networks. This approach enhances the engineering applicability and data compatibility of the model and provides reliable mesoscopic thermodynamic data support for cross-scale coordinated optimization.

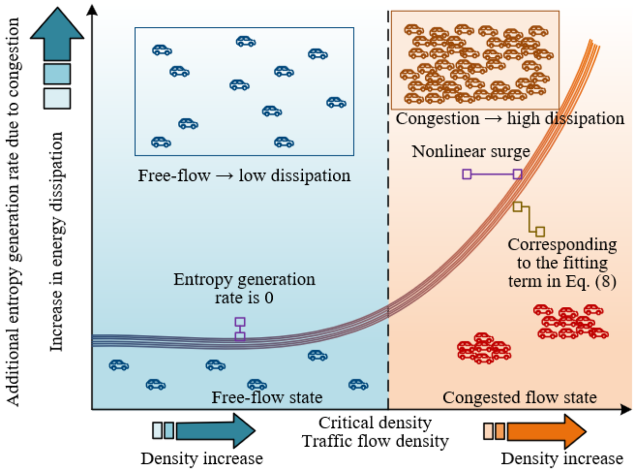


Figure 2. Relationship between nonequilibrium steady-state phase transition in traffic flow and the evolution of congestion-induced entropy

2.4 Thermodynamic characterization model of logistics network topology

Conventional macroscopic logistics network modeling has predominantly relied on graph-theoretic approaches, focusing on node layout and path geometric characteristics, while neglecting the thermodynamic constraints imposed by topological disorder on energy dissipation. As a result, network optimization lacks a physical theoretical foundation and cannot fundamentally improve global energy efficiency. From the perspective of nonequilibrium statistical mechanics, a thermodynamic characterization model of logistics network topology is developed to overcome the limitations of traditional graph-theoretic methods. The core innovations are concentrated on three-dimensional structural entropy modeling, the coupling of operational entropy and spatial entropy, the construction of a global exergy balance, and the formulation of topology optimization criteria. Through this framework, a unified thermodynamic quantification of macroscopic logistics network structure and energy dissipation is achieved, thereby addressing the gap in thermodynamic modeling at the macroscopic scale. For structural entropy modeling, the logistics network is represented as a weighted directed graph, in which nodes correspond to distribution centers and customer locations, and edges represent road connections with weights defined by travel distance. Based on an extension of Shannon entropy, a three-dimensional structural entropy model is constructed by integrating node degree distribution, edge weight distribution, and clustering coefficients. The expression is given as:

$$S_{struct}=-\alpha\sum_{i=1}^{N}p\left(k_i\right)\ln p\left(k_i\right)-\beta\sum_{j=1}^{M}p\left(w_j\right)\ln p\left(w_j\right)-\gamma\sum_{i=1}^{N}C_i\ln C_i \tag{11}$$

where, S_{struc} denotes structural entropy, $p(k_i)$ represents the probability distribution of node degree, $p(w_j)$ denotes the probability distribution of edge weights, and C_i is the clustering coefficient of node. The weighting coefficients α, β, and γ satisfy $\alpha+\beta+\gamma=1$. This model overcomes the limitation of single-dimensional entropy characterization and enables accurate quantification of node distribution uniformity and path redundancy. A higher structural entropy indicates a more disordered network topology, which increases the probability of empty travel and detours, thereby revealing the thermodynamic constraint of network structure on energy dissipation.

For operational entropy modeling, attention is focused on the spatial distribution characteristics of energy dissipation within the network. By incorporating the distance-normalized entropy generation coefficients obtained from the mesoscopic model, a network-level operational entropy model is constructed. In addition, spatial entropy is introduced to quantify the uniformity of exergy dissipation distribution. The operational entropy is expressed as:

$$S_{oper}=\sum_{j=1}^{M}\eta_{road,j}\cdot w_j \tag{12}$$

The spatial entropy is expressed as:

$$S_{space}=-\sum_{j=1}^{M}\frac{\eta_{road,j}}{\sum_{j=1}^{M}\eta_{road,j}}\ln\frac{\eta_{road,j}}{\sum_{j=1}^{M}\eta_{road,j}} \tag{13}$$

where, $\eta_{road,j}$ denotes the distance-normalized entropy generation coefficient of road segment j, and w_j represents the weight of the corresponding road segment. Through the coupling of operational entropy and spatial entropy, high-entropy-generation nodes and road segments within the network can be accurately identified, thereby revealing the spatial aggregation characteristics of energy dissipation. For global exergy balance, a macroscopic exergy balance equation is established as:

$$E_{in}=E_{min}+\sum_{s=1}^{3}E_{loss,s}+E_{waste} \tag{14}$$

where, E_{in} denotes the total exergy input to the system, E_{min} represents the minimum exergy required to complete the delivery tasks, $E_{loss,s}$ corresponds to irreversible exergy losses at the microscopic, mesoscopic, and macroscopic scales, and E_{waste} denotes the exergy discharged from the system. Based on this formulation, the entropy generation contribution rate is defined to identify the dominant scales and nodes responsible for system energy degradation, thereby providing a clear basis for subsequent optimization:

$$\delta_s=\frac{E_{loss,s}}{\sum_{t=1}^{3}E_{loss,t}} \tag{15}$$

For topology optimization, a network adjustment criterion based on structural entropy minimization is proposed. Thermodynamic order is incorporated as a constraint in distribution center location selection and route planning. By minimizing the structural entropy S_{struc}, node distribution and path redundancy are optimized. This approach overcomes the limitation of traditional network optimization methods that focus solely on geometric and temporal constraints without considering physical principles. As a result, thermodynamic optimization of macroscopic logistics network topology is achieved, providing a structural foundation for global energy efficiency improvement.

3. CROSS-SCALE COORDINATED OPTIMIZATION MECHANISM

3.1 Dual-layer iterative optimization structure

Conventional urban logistics optimization has predominantly adopted single-level and single-objective designs, focusing on independent optimization of routing or driving strategies. As a result, coordinated interaction across microscopic, mesoscopic, and macroscopic scales cannot be achieved. Furthermore, optimization objectives have typically been limited to minimizing distance or time, making it difficult to reduce system entropy generation from a fundamental thermodynamic perspective. To overcome these limitations, a dual-layer iterative optimization framework integrating the physical layer and the logistics layer is established. The core innovation lies in adopting global entropy generation minimization as the central objective, enabling deep coordination among microscopic driving strategies, mesoscopic traffic states, and macroscopic route scheduling. Through a thermodynamic consistency–based iterative mechanism, cross-scale coupling inconsistencies are resolved, thereby enhancing both the scientific rigor and effectiveness of the optimization process. The overall dual-layer iterative optimization procedure is illustrated in Figure 3. The inner-layer physical optimization focuses on minimizing entropy generation within the microscopic powertrain. Under fixed routing and time constraints provided by the outer layer, the instantaneous entropy generation rate of the vehicle is minimized to determine the optimal velocity trajectory under transient operating conditions. The optimization model is formulated using the calculus of variations and the Pontryagin minimum principle, and the Hamiltonian is defined as:

$$H=\dot{S}_{micro}+\lambda_1\dot{x}+\lambda_2\ddot{x} \tag{16}$$

where, $\dot{S}_{micro}$ denotes the instantaneous entropy generation rate at the microscopic scale, $\dot{x}$ represents vehicle speed, $\ddot{x}$ denotes acceleration, and λ_1 and λ_2 are costate variables. By solving the corresponding costate equations and boundary conditions, the optimal velocity trajectory is obtained. At the same time, the minimum exergy consumption for each road segment, denoted as $E_{micro,min}$, is calculated, providing high-precision microscopic thermodynamic cost information for the outer-layer optimization. To improve computational efficiency and real-time applicability, an adaptive step-size numerical method is employed in the inner layer. The step size is dynamically adjusted according to variations in entropy generation rate, thereby achieving a balance between solution accuracy and computational efficiency. This approach meets the requirements in dynamic urban logistics scheduling scenarios.

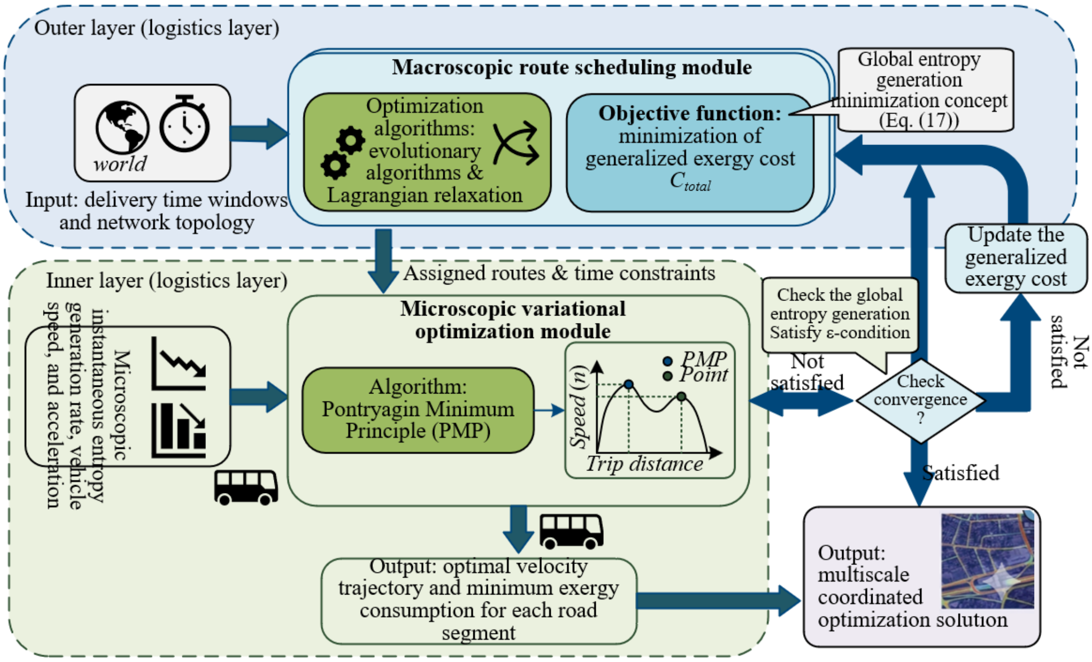


Figure 3. Dual-layer iterative optimization process with global entropy generation minimization as the objective

The outer-layer logistics optimization is designed to achieve coordinated interaction between macroscopic route scheduling and mesoscopic traffic states. The core innovation lies in the construction of a generalized exergy cost function, through which the optimization objective is upgraded from conventional distance or time minimization to global entropy generation minimization. The generalized exergy cost function integrates the minimum exergy consumption of each road segment obtained from the inner layer, the congestion-induced entropy from the mesoscopic model, and the time-related exergy loss. It is expressed as:

$$C_{total}=\sum_{j=1}^{M}\left(E_{micro,min,j}+\omega_1 S_{cong,j}+\omega_2 E_{time,j}\right) \tag{17}$$

where, C_{total} denotes the global generalized exergy cost; $E_{micro,min,j}$ represents the minimum exergy consumption of road segment j; $S_{cong,j}$ denotes the congestion-induced entropy; $E_{time,j}$ represents the time-related exergy loss; and ω_1 and ω_2 are weighting coefficients. Through this formulation, multiscale thermodynamic costs are quantified in a coordinated manner. The outer layer adopts this function as the optimization objective and solves a vehicle routing problem with time windows. Algorithmic innovation is achieved through a hybrid approach combining evolutionary algorithms and Lagrangian relaxation. The time window constraints are transformed into penalty terms via Lagrangian relaxation, thereby reducing problem complexity, while evolutionary algorithms are employed to achieve global optimization, improving computational efficiency under high-dimensional constraints. The iterative coupling mechanism constitutes the core support of the framework. A thermodynamic consistency–based iterative strategy is designed, in which the routing scheme generated by the outer layer is transmitted to both the inner layer and the mesoscopic model. The inner layer computes the minimum exergy consumption for each road segment, while the mesoscopic model updates the corresponding congestion-induced entropy. These outputs are jointly fed back to the outer layer to update the generalized exergy cost function. The process is repeated iteratively until the global entropy generation satisfies the convergence condition:

$$|S_{total,k+1}-S_{total,k}|<\varepsilon \tag{18}$$

where, $S_{total,k}$ denotes the global entropy generation at the k-th iteration, and ε is the convergence threshold. Through this process, multiscale coordinated optimization is achieved, overcoming the limitations of conventional approaches characterized by hierarchical separation and restricted optimization objectives.

3.2 Virtual exergy pricing–based coordinated regulation via exergy loss decoupling

Conventional urban logistics scheduling has largely relied on empirical rules and geometric path information, while lacking perception and quantitative characterization of the system's thermodynamic state. As a result, precise coordinated regulation across multiple scales cannot be achieved, and optimization performance is difficult to sustain. To overcome these limitations, a dynamic regulation mechanism based on thermodynamic state awareness is established. The core innovations are centered on multiscale exergy loss decoupling, dynamic modeling of virtual exergy pricing, multiscale coordinated regulation strategies, and closed-loop control design. Through this framework, deep coordination between physical-layer energy consumption and control-layer scheduling is achieved, thereby enhancing both the precision and dynamic adaptability of the regulation process (Figure 4). The decoupling of exergy losses serves as the foundation of the regulation mechanism. A multiscale exergy loss decomposition method is proposed, through which the total system exergy loss is decomposed into three components: microscopic powertrain irreversibility losses, mesoscopic additional dissipation due to traffic congestion, and macroscopic losses associated with network structural disorder. The decomposition is expressed as:

$$E_{loss}=E_{loss,micro}+E_{loss,meso}+E_{loss,macro} \tag{19}$$

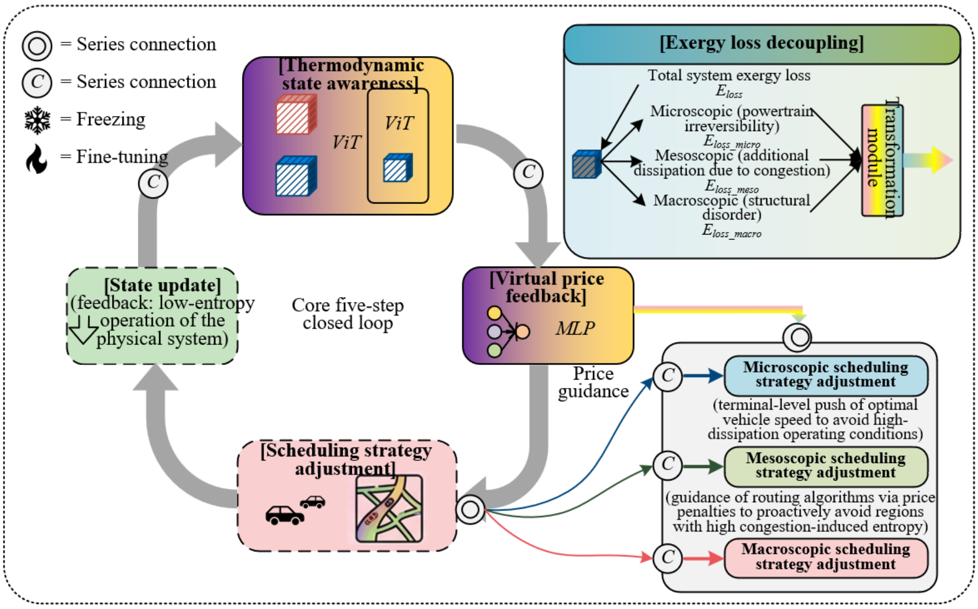


Figure 4. Closed-loop coordinated regulation based on virtual exergy pricing driven by thermodynamic state awareness

where, E_{loss} denotes the total system exergy loss, $E_{loss,micro}$ represents microscopic exergy loss due to powertrain irreversibility, $E_{loss,meso}$ corresponds to additional exergy dissipation induced by congestion at the mesoscopic scale, and $E_{loss,macro}$ denotes exergy loss associated with macroscopic network structural disorder. Based on this decomposition, sensitivity analysis and entropy generation contribution rate calculations are performed to define the entropy generation contribution ratio. This metric enables accurate identification of dominant dissipation sources responsible for system energy degradation, thereby providing a quantitative basis for targeted regulation and overcoming the limitation of conventional approaches that fail to locate critical dissipation mechanisms.

$$\dot{\delta}_s=\frac{E_{loss,s}}{E_{loss}} \tag{20}$$

where, s corresponds to the microscopic, mesoscopic, and macroscopic scales, respectively.

The innovation of virtual exergy pricing establishes a quantitative linkage between thermodynamic states and scheduling decisions. The unit exergy loss rate under varying spatiotemporal conditions is transformed into a monetized virtual exergy price, and a dynamic updating model is constructed as:

$$p_{ex}(t,x)=k_{ex}\cdot\frac{\dot{E}_{loss}(t,x)}{\dot{E}_{ref}} \tag{21}$$

where, $p_{ex}(t,x)$ denotes the virtual exergy price at time t and road segment x; k_{ex} is the price adjustment coefficient; $\dot{E}_{loss}(t,x)$ represents the exergy loss rate per unit time and per unit distance; and $\dot{E}_{ref}$ is the reference exergy loss rate. This model enables real-time reflection of the spatiotemporal variations in thermodynamic states of road segments, thereby providing a unified quantitative basis for multiscale regulation. Multiscale coordinated regulation strategies are developed based on virtual exergy pricing, enabling synergistic interaction across microscopic, mesoscopic, and macroscopic levels. At the microscopic level, real-time virtual exergy prices are utilized to generate optimal driving speed profiles, which are delivered to vehicle terminals to guide drivers in avoiding high exergy loss operating conditions. Simultaneously, driving behavior data are fed back to the fleet management system, forming a closed-loop microscopic regulation mechanism. At the mesoscopic level, the price adjustment coefficient k_{ex} is dynamically increased in regions characterized by high congestion-induced entropy. Through price signals, routing algorithms are guided to proactively avoid such regions. In parallel, optimization of microscopic driving behavior reduces velocity fluctuations, thereby enhancing traffic flow stability and suppressing congestion-induced entropy generation. At the macroscopic level, distribution sequences and routing schemes are dynamically adjusted based on the spatial distribution of virtual exergy prices. This approach balances time window constraints with global entropy generation minimization, thereby achieving thermodynamic optimization of macroscopic scheduling.

To enhance dynamic adaptability, a closed-loop control system is established, following the logical sequence: thermodynamic state awareness → exergy loss decoupling → virtual price feedback → scheduling strategy adjustment → state update. Thermodynamic state data across all scales are continuously collected, and both exergy loss decomposition and virtual exergy pricing are dynamically updated. Regulation strategies are iteratively refined to achieve seamless coordination between the physical layer and the control layer. Through this mechanism, the regulation framework is enabled to adapt to dynamic changes in urban logistics systems, thereby maintaining a low-entropy-generation operating state from a fundamental thermodynamic perspective.

4. MODEL VALIDATION AND EXPERIMENTAL DESIGN

4.1 Validation scheme design

To comprehensively evaluate the accuracy, rationality, and applicability of the proposed multiscale thermodynamic modeling and optimization framework for urban logistics systems, a three-level validation strategy was established, following the logical sequence of single-scale model accuracy, cross-scale coupling consistency, and overall optimization performance. By integrating simulation experiments with real-vehicle validation, a multi-scenario and multi-metric validation system was constructed to ensure methodological rigor and innovation, in accordance with the standards required by leading international Science Citation Index (SCI) journals.

At the microscopic level, model validation was conducted through a combination of AVL Cruise simulations and real-world vehicle tests. Representative transient operating conditions in urban logistics were selected, and the predictive performance of the proposed model was compared with that of conventional steady-state models. Through this approach, the capability of the proposed model to accurately capture entropy generation under transient conditions was demonstrated. For mesoscopic–macroscopic coupling validation, two representative urban scenarios were selected, namely urban core areas and logistics park regions. Based on road network data obtained from OpenStreetMap and floating vehicle trajectory data from the Didi GAIA platform, realistic traffic flow environments were constructed using Simulation of Urban MObility (SUMO) simulation, enabling validation of the rationality of the congestion-induced entropy model and its amplification effect on microscopic entropy generation. For overall optimization validation, comparative experiments were designed in which the proposed global entropy generation minimization strategy was quantitatively evaluated against conventional shortest-distance and shortest-time optimization strategies. This comparison allows the advantages of the proposed optimization mechanism to be clearly identified. In addition, sensitivity analysis was conducted under varying urban forms and distribution modes to investigate the variation patterns of entropy generation contribution rates across different scales. Through this analysis, the adaptability of the proposed model to diverse application scenarios was verified. All experimental data collection and processing procedures were conducted in accordance with thermodynamic experimental standards to ensure data authenticity and reliability, thereby providing a solid foundation for model validation.

The experimental study was conducted in two representative regions of a typical second-tier city. The first region corresponded to the urban core area, covering approximately 15 km² and comprising 23 distribution nodes and 47 road segments. The second region corresponded to a peripheral logistics park, covering approximately 8 km² and including 12 distribution nodes and 28 road segments. Four representative urban logistics vehicles were selected for real-world testing, including two internal combustion engine vehicles and two battery electric vehicles. The vehicle parameters were specified as follows: total mass of 4.5 t, frontal area of 3.2 m², rolling resistance coefficient of 0.018, and aerodynamic drag coefficient of 0.65. For simulation and computational analysis, AVL Cruise 2023 was employed for microscopic vehicle modeling, while SUMO 1.18.0 was utilized for traffic flow simulation at the mesoscopic scale. Numerical optimization and algorithm implementation were conducted using MATLAB R2023b. Multiple data sources were integrated. Floating vehicle trajectory data were obtained from the Didi GAIA platform, with a sampling frequency of 1 Hz. Road network data were derived from OpenStreetMap. In addition, real-world vehicle testing data, including vehicle speed, acceleration, and fuel or electricity consumption, were collected with a sampling frequency of 0.5 Hz. The experimental campaign was conducted over a period of 15 consecutive days, during which continuous data were collected for 12 hours per day, spanning from 07:00 to 19:00.

4.2 Experimental results and analysis

The validation of the microscopic model was focused on the predictive accuracy of instantaneous entropy generation rate and exergy loss under transient operating conditions. Three representative urban logistics operating conditions were selected, namely acceleration–deceleration, idling, and braking. The predictions of the proposed finite-time thermodynamic improved model were compared with those of a conventional steady-state efficiency map–based model, and both were further validated against real-world vehicle measurement data. The results are summarized in Table 1.

As shown in Table 1, the proposed microscopic model exhibits significantly higher predictive accuracy than the conventional steady-state model under all representative operating conditions. The relative error of the instantaneous entropy generation rate predicted by the proposed model is consistently controlled within 5%, with an average value of

3.1%, while the average relative error of exergy loss is 3.0%. These results indicate that multi-source irreversible losses within the powertrain under transient operating conditions can be accurately captured. In contrast, the conventional steady-state model demonstrates relative errors generally exceeding 10%, with an average value of 18.3%. Due to its reliance on steady-state assumptions, it is unable to adapt to transient operating conditions characterized by frequent acceleration, deceleration, and idling, and therefore fails to accurately quantify instantaneous entropy generation and exergy loss. The experimental results confirm that the proposed finite-time thermodynamic improved model effectively eliminates the limitations associated with steady-state assumptions by incorporating a differential formulation of instantaneous entropy generation and a coupled vehicle longitudinal dynamics–thermodynamics model. As a result, the entropy generation mechanisms under transient operating conditions are accurately characterized, providing high-fidelity microscopic thermodynamic data to support cross-scale coupling. The accuracy and innovation of the microscopic model are thus validated.

For mesoscopic–macroscopic coupling validation, emphasis was placed on verifying the rationality of the congestion-induced entropy model and its amplification effect on microscopic entropy generation. Two representative regions, namely the urban core area and the logistics park, were selected. Three traffic states—free flow, moderate congestion, and severe congestion—were simulated. The congestion-induced entropy and the distance-normalized entropy generation coefficient obtained from simulation were compared with measured data, and the amplification effect of congestion on microscopic entropy generation was analyzed. The corresponding results are presented in Table 2.

Table 1. Comparison of prediction accuracy for the microscopic model

Operating Condition	**Acceleration–Deceleration**	**Idling**	**Braking**	**Average**
Vehicle speed range (km/h)	0–40	0	40–0	-
Acceleration range (m/s^2)	-2.5–3.0	0	-4.0–0	-
Instantaneous entropy generation rate (proposed model) ($\times 10^{-3}$ W/(kg·K))	8.2–15.6	3.1–3.5	16.8–22.3	-
Instantaneous entropy generation rate (conventional model) ($\times 10^{-3}$ W/(kg·K))	6.1–12.3	1.8–2.2	12.5–17.1	-
Measured instantaneous entropy generation rate ($\times 10^{-3}$ W/(kg·K))	7.9–15.2	3.0–3.4	16.2–21.8	-
Relative error of the proposed model (%)	2.3–4.8	1.9–3.2	2.5–4.5	3.1
Relative error of the conventional model (%)	10.5–18.7	22.6–30.1	11.2–19.3	18.3
Exergy loss (proposed model) (kJ)	128.6–245.3	46.5–52.5	252.0–334.5	-
Exergy loss (conventional model) (kJ)	98.2–192.7	27.0–33.0	187.5–256.5	-
Relative error of exergy loss (%)	2.1–5.2	2.0–3.5	2.3–4.7	3.0

Table 2. Comparison of mesoscopic–macroscopic coupling validation results

Experimental Region	**Core Area**			**Logistics Park**		
Traffic state	Free flow	Moderate congestion	Severe congestion	Free flow	Moderate congestion	Severe congestion
Traffic density (veh/km)	20–50	50–100	>100	10–30	30–60	>60
Average speed (km/h)	45–60	20–45	<20	50–70	30–50	<30
Simulated congestion-induced entropy (J/(kg·K))	12.3–15.6	28.7–35.4	89.2–105.6	8.5–11.2	19.6–26.3	56.8–72.4
Measured congestion-induced entropy (J/(kg·K))	11.9–15.2	27.9–34.6	87.5–103.2	8.2–10.9	19.0–25.7	55.6–70.8
Relative error of congestion entropy (%)	2.1–2.8	2.4–2.9	1.9–2.3	2.3–2.7	2.5–2.7	2.0–2.3
Distance-normalized entropy generation coefficient ($\times 10^{-3}$ W/(kg·K·m))	0.8–1.2	2.1–2.8	6.5–8.2	0.5–0.9	1.4–2.0	4.2–5.8
Measured coefficient ($\times 10^{-3}$ W/(kg·K·m))	0.78-1.17	2.05–2.73	6.37–8.04	0.48–0.87	1.37–1.96	4.12–5.70
Relative error of coefficient (%)	2.3–2.6	2.2–2.6	1.9–2.2	2.4–3.0	2.1–2.3	1.9–2.1
Amplification factor of microscopic entropy generation	1.0–1.2	2.3–2.9	6.8–8.5	1.0–1.1	1.8–2.4	4.5–5.9

As shown in Table 2, the proposed congestion-induced entropy model demonstrates high predictive accuracy. The relative errors of both congestion-induced entropy and the distance-normalized entropy generation coefficient are consistently maintained within 3%, thereby confirming the validity and reliability of the model. As traffic conditions transition from free-flow to congested states, both congestion-induced entropy and the distance-normalized entropy generation coefficient exhibit a pronounced increasing trend. Correspondingly, the amplification factor of microscopic entropy generation increases significantly. Under severe congestion conditions, the amplification factor reaches 6.8–8.5 in the urban core area and 4.5–5.9 in the logistics park. These results indicate that congestion exerts a substantial amplification effect on microscopic entropy generation, which is consistent with the proposed concept that congestion-induced entropy quantitatively characterizes additional dissipation. Furthermore, both congestion-induced entropy and the amplification factor of microscopic entropy generation are observed to be consistently higher in the urban core area than in the logistics park. This difference is attributed to the higher road network density and more frequent vehicle interactions in the core area, which result in more pronounced additional dissipation under congested conditions. These findings further validate the capability of the congestion-induced entropy model to accurately capture mesoscopic dissipation characteristics under varying traffic conditions and across different urban regions. Overall, effective coupling between mesoscopic and microscopic scales is achieved, and reliable mesoscopic thermodynamic support is provided for subsequent cross-scale optimization.

For overall optimization validation, the performance of the proposed global entropy generation minimization strategy was compared with conventional shortest-distance and shortest-time strategies. Key performance indicators, including exergy efficiency, total energy consumption, energy consumption reduction rate, and related thermodynamic metrics, were selected to quantitatively evaluate the advantages of the proposed optimization mechanism. The results are summarized in Table 3.

Table 3. Comparison of overall optimization performance

Optimization Strategy	Proposed Strategy	Shortest Distance	Shortest Time
Exergy efficiency (%)	78.6	68.3	65.8
Total energy consumption (L/100 km)	8.2	9.7	10.3
Energy consumption reduction rate (%)	15.3	-	-
On-time delivery rate (%)	92.5	81.2	93.1
Spatial uniformity of entropy generation	0.87	0.62	0.58
Number of iterations to convergence	18	-	-
Convergence time (s)	24.6	-	-
Global entropy generation (×10^3 J/(kg·K))	42.3	58.7	63.5
Generalized exergy cost (CNY)	128.5	142.3	151.7

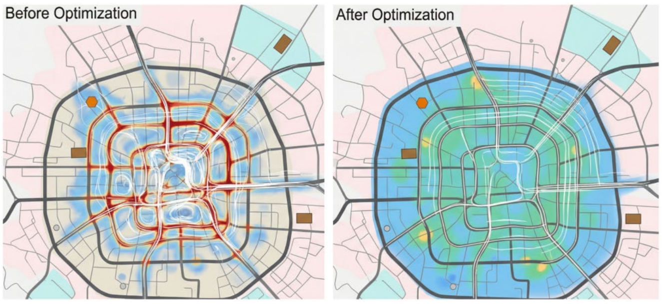
Table 4. Sensitivity analysis results

Urban Form	Single-Center		Multi-Center	
Distribution mode	On-demand delivery	Scheduled delivery	On-demand delivery	Scheduled delivery
Contribution of microscopic entropy generation (%)	32.6	30.2	35.8	33.5
Contribution of mesoscopic entropy generation (%)	48.3	45.7	36.2	33.8
Contribution of macroscopic entropy generation (%)	19.1	24.1	28.0	32.7
Total exergy loss (×10^3 kJ)	87.5	79.3	75.6	68.9
Optimal virtual exergy price coefficient	1.25	1.18	1.32	1.27
Exergy efficiency (%)	76.8	79.2	80.5	82.3
Energy consumption reduction rate (%)	14.8	16.2	17.5	19.1

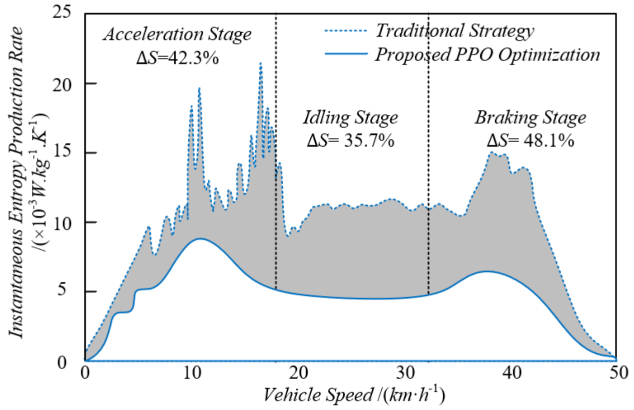
As shown in Table 3, the proposed global entropy generation minimization strategy demonstrates superior performance across all key evaluation metrics. Compared with the conventional shortest-distance strategy, exergy efficiency is improved by 10.3 percentage points, total energy consumption is reduced by 15.3%, global entropy generation is decreased by 27.9%, and the spatial uniformity of entropy generation is enhanced by 40.3%. In addition, the on-time delivery rate is increased by 11.3 percentage points. When compared with the conventional shortest-time strategy, exergy efficiency is improved by 12.8 percentage points, total energy consumption is reduced by 20.4%, global entropy generation is decreased by 33.4%, and the spatial uniformity of entropy generation is enhanced by 49.7%, while the on-time delivery rate remains comparable. These results indicate that the proposed dual-layer iterative optimization framework, together with the generalized exergy cost function, effectively integrates microscopic exergy losses, mesoscopic congestion-induced entropy, and macroscopic structural entropy by adopting global entropy generation minimization as the core objective. As a result, coordinated optimization across multiple scales is successfully achieved. Furthermore, the number of iterations required for convergence is controlled within 20, and the convergence time remains relatively short, demonstrating that the proposed framework is capable of meeting the requirements of dynamic logistics scheduling. This finding confirms the computational efficiency of both the optimization framework and the associated algorithms. In addition, the generalized exergy cost obtained using the proposed strategy is lower than that of conventional strategies, indicating that improvements in energy efficiency are achieved without sacrificing economic performance. This result further highlights the engineering applicability and innovative advantages of the proposed optimization mechanism.

For sensitivity analysis, variations in entropy generation contribution rates across different scales were investigated under different urban configurations (single-center and multi-center structures) and distribution modes (on-demand delivery and scheduled delivery). Through this analysis, the adaptability of the proposed model to diverse scenarios was evaluated. The corresponding results are presented in Table 4.

As shown in Table 4, significant variations in entropy generation contributions across different scales are observed under different urban forms and distribution modes, thereby confirming the adaptability of the proposed model to diverse scenarios. In single-center cities, the mesoscopic entropy generation contribution is dominant (45.7%–48.3%), indicating that severe traffic congestion leads to mesoscopic traffic flow dissipation being the primary driver of system energy degradation. In contrast, in multi-center cities, the macroscopic entropy generation contribution increases significantly (28.0%–32.7%), exceeding that of single-center configurations. This finding suggests that the structural disorder of logistics network topology plays a more prominent role in energy dissipation, which is consistent with the proposed concept that structural entropy quantitatively characterizes network disorder. With respect to distribution modes, the contributions of microscopic and mesoscopic entropy generation are higher in on-demand delivery scenarios than in scheduled delivery scenarios, whereas the macroscopic entropy generation contribution is higher in scheduled delivery. This behavior can be attributed to the higher operational frequency and more complex driving conditions associated with on-demand delivery, while scheduled delivery relies more heavily on route planning and node coordination within the network structure. In addition, variations in the optimal virtual exergy price coefficient across different scenarios are observed, indicating that the proposed dynamic virtual exergy pricing model is capable of adapting to changes in thermodynamic states under diverse conditions. This result further confirms the dynamic adaptability of the coordinated regulation mechanism. Overall, the experimental results demonstrate that the proposed multiscale thermodynamic modeling and optimization framework can effectively adapt to different urban forms and distribution modes. The approach exhibits strong generality and provides a flexible theoretical and technical foundation for improving energy efficiency in urban logistics systems under a wide range of practical scenarios.



(a) Global entropy generation spatial distribution heatmaps of the urban logistics network before and after optimization



(b) Comparative curves of vehicle speed versus entropy generation rate for representative road segments at the microscopic scale

Figure 5. Final visualization results of the image processing

To evaluate the effectiveness of the proposed multiscale thermodynamic modeling and optimization mechanism in regulating energy dissipation within urban logistics systems, comparative experiments were conducted at both the macroscopic network level and the microscopic dynamic level. The corresponding results are presented in Figure 5. At the macroscopic network level, prior to optimization, contiguous high-entropy-generation regions are observed to form at intersections and bottleneck road segments within the urban core area. Vehicle trajectories exhibit pronounced congestion vortices and highly uneven spatial distributions, indicating that energy dissipation is strongly concentrated and that thermodynamic disorder is significant under conventional logistics scheduling. After optimization, high-entropy-generation regions are largely eliminated, and the global entropy distribution is dominated by low-entropy (blue–green) regions. Vehicle trajectories become more evenly distributed and spatially balanced. A reduction in entropy generation exceeding 60% is achieved in the core area, providing direct evidence that macroscopic structural entropy optimization and virtual exergy pricing–based regulation effectively alleviate high-dissipation regions and enhance thermodynamic order at the system level.

At the microscopic dynamic level, under conventional driving strategies, the entropy generation rate exhibits strong fluctuations, with sharp peaks observed during acceleration, idling, and braking phases, reflecting significant irreversible losses under transient operating conditions. In contrast, under the proposed proximal policy optimization (PPO) strategy, the entropy generation rate profile becomes smooth and stable, with substantial reductions in peak values. Specifically, entropy generation is reduced by 42.3%, 35.7%, and 48.1% during acceleration, idling, and braking phases, respectively. These results demonstrate that the integration of the transient finite-time thermodynamic model with microscopic driving optimization effectively suppresses multi-source irreversible losses in the powertrain, thereby achieving fundamental improvements in microscopic energy efficiency. Overall, the proposed multiscale thermodynamic modeling and optimization framework enables coordinated reduction of entropy generation across both macroscopic network structures and microscopic vehicle dynamics. Significant improvements in global energy efficiency are thus achieved, providing a robust thermodynamic theoretical and technological foundation for promoting green and low-carbon development in urban logistics systems.

Based on the comprehensive experimental results, the proposed multiscale thermodynamic modeling and energy efficiency optimization mechanism for urban logistics systems demonstrates high accuracy, rationality, and applicability. At the microscopic level, entropy generation and exergy loss mechanisms under transient operating conditions are accurately characterized, with predictive performance significantly exceeding that of conventional models. At the mesoscopic–macroscopic level, the proposed coupling model effectively quantifies the amplification effect of congestion on microscopic entropy generation, enabling precise characterization of thermodynamic interactions across multiple scales. At the system level, the proposed optimization strategy successfully achieves global entropy generation minimization and outperforms conventional approaches in terms of energy efficiency, economic performance, and on-time delivery rate. In addition, strong adaptability is demonstrated across different urban forms and distribution modes, indicating robust scenario generalization capability. These experimental findings provide comprehensive validation of the scientific soundness and practical value of the proposed methodological innovations. Furthermore, a reliable experimental foundation is established for achieving fundamental improvements in energy efficiency within urban logistics systems. At the same time, the application framework of nonequilibrium thermodynamics in complex engineering systems is further extended and enriched.

5. DISCUSSION

The proposed multiscale thermodynamic modeling and energy efficiency optimization mechanism for urban logistics systems is closely aligned with current research frontiers concerning the application of nonequilibrium thermodynamics in complex engineering systems. A deep integration of nonequilibrium thermodynamic theory with urban logistics engineering practice is achieved, demonstrating significant academic value in both theoretical advancement and technological innovation. From a theoretical perspective, the limitations of conventional single-scale thermodynamic analysis are overcome through the construction of a three-layer nested bidirectional coupling framework spanning microscopic, mesoscopic, and macroscopic levels. A three-dimensional entropy characterization system, comprising structural entropy, operational entropy, and congestion-induced entropy, is established, thereby advancing the theoretical understanding of multiscale entropy generation coupling in complex engineering systems. Existing applications of nonequilibrium thermodynamics have predominantly focused on single-scale analyses or unidirectional coupling relationships, making it difficult to capture feedback interactions across multiple scales. In contrast, seamless transmission of entropy generation information across scales is enabled through the introduction of thermodynamic consistency criteria and carefully designed coupling variables. Through this approach, the principle of entropy generation minimization is extended from microscopic physical processes to macroscopic logistics decision-making. As a result, the application scope of nonequilibrium thermodynamics in complex networked systems is significantly broadened, and a novel theoretical paradigm is provided for thermodynamic modeling in similar engineering systems.

From the perspective of engineering applications of exergy analysis, the limitations of conventional approaches—primarily confined to single-device energy efficiency evaluation—are overcome. Exergy analysis is systematically integrated throughout the entire multiscale modeling and optimization process. A generalized exergy cost function and a dynamic virtual exergy pricing model are constructed, enabling a quantitative linkage between thermodynamic states and scheduling decisions. In this manner, the transition of exergy analysis from theoretical investigation to practical engineering application is effectively promoted. In comparison with existing studies on urban logistics energy efficiency optimization, the proposed methodological innovations demonstrate substantial performance improvements. In prior multiscale optimization studies, energy consumption reduction rates are typically reported within the range of 8%–12%. In contrast, the proposed global entropy generation minimization strategy achieves energy consumption reductions of 15.3%–20.4%, exergy efficiency improvements of 10.3%–12.8%, and reductions in global entropy generation of 27.9%–33.4%. These results indicate that three major technical bottlenecks—namely, the limitations of conventional optimization objectives, inconsistencies in cross-scale coupling, and difficulties in identifying dominant dissipation sources—are effectively addressed. Beyond its practical implications, the present framework provides a thermodynamic first-principles foundation for improving energy efficiency in urban logistics systems. At the same time, the engineering application boundaries of nonequilibrium thermodynamics are further expanded, facilitating deeper interdisciplinary integration with logistics engineering, transportation engineering, and related fields. This work is therefore well aligned with the core requirements of leading international thermodynamics journals, which emphasize the integration of theoretical innovation and engineering application.

Despite these advances in multiscale thermodynamic modeling and optimization, several limitations remain, providing clear directions for future research. First, the influence of extreme weather conditions on system entropy generation is not considered. Conditions such as heavy rainfall, high temperatures, and severe cold can significantly affect vehicle powertrain efficiency, road friction coefficients, and traffic flow states, thereby altering entropy generation characteristics. Consequently, the current model is primarily applicable to standard operating conditions. Second, the calibration accuracy of the monetary representation of virtual exergy pricing remains to be improved. The current model defines the price regulation coefficient based on a reference exergy loss rate, without fully accounting for variations in energy prices and logistics costs across different cities, which may affect regional adaptability. Finally, the effects of vehicle powertrain aging on irreversible losses are not incorporated. Long-term operation leads to performance degradation of the powertrain, which may reduce the predictive accuracy of entropy generation models. Therefore, further development is required to enhance the long-term adaptability of the proposed framework.

In light of the aforementioned limitations and in alignment with emerging research frontiers in thermodynamics-oriented journals, future research can be advanced along four key directions. First, multiscale thermodynamic modeling of multi-energy logistics vehicles should be developed. For emerging vehicle types such as hybrid electric and hydrogen-powered logistics vehicles, entropy generation models encompassing multi-energy conversion processes should be constructed to enhance energy adaptability and further expand the application of nonequilibrium thermodynamics in new energy engineering systems. Second, real-time regulation systems based on digital twin technology should be established. By integrating Internet of Things and big data technologies, a thermodynamic digital replica of urban logistics systems can be constructed, enabling real-time perception, prediction, and regulation of thermodynamic states. Such an approach is expected to significantly enhance the dynamic responsiveness of the proposed optimization mechanism. Third, thermodynamic optimization should be extended to inter-city logistics networks. By overcoming the limitations of single-city studies, cross-regional multiscale thermodynamic coupling models can be developed to investigate entropy generation mechanisms in inter-regional logistics coordination, thereby providing theoretical support for green and low-carbon development of regional logistics systems. Fourth, deeper integration between machine learning and finite-time thermodynamic theory should be pursued. Machine learning algorithms can be employed to optimize entropy generation model parameters, thereby improving predictive accuracy under transient operating conditions. At the same time, adaptive calibration of virtual exergy pricing can be achieved, further enhancing cross-scale coordinated regulation mechanisms. This integration is expected to promote interdisciplinary innovation between thermodynamic theory and artificial intelligence, providing more efficient theoretical frameworks and technical methodologies for energy efficiency optimization in complex engineering systems.

6. CONCLUSION

In response to the critical challenges—unclear energy dissipation mechanisms and the lack of cross-scale coordinated optimization in urban logistics systems—this study was conducted with nonequilibrium thermodynamics as the theoretical foundation, focusing on multiscale entropy generation coupling and global energy efficiency optimization. The predefined research objectives were successfully achieved, and the principal findings and contributions are summarized below.

Significant innovations have been realized in both multiscale thermodynamic modeling and optimization mechanisms, resulting in the establishment of a comprehensive theoretical and technical framework. At the modeling level, the limitations of conventional single-scale and unidirectional modeling approaches have been overcome through the construction of a three-layer nested bidirectional coupling thermodynamic framework spanning microscopic, mesoscopic, and macroscopic scales. A three-dimensional entropy characterization system, consisting of structural entropy, operational entropy, and congestion-induced entropy, has been proposed, enabling unified thermodynamic quantification of network structural disorder, traffic flow dissipation, and powertrain irreversible losses in urban logistics systems. At the microscopic level, an improved finite-time thermodynamic model under transient operating conditions has been developed, allowing precise characterization of multi-source irreversible entropy generation mechanisms. At the mesoscopic level, a congestion-induced entropy model based on nonequilibrium steady-state traffic flow has been constructed, revealing the amplification effect of congestion on microscopic entropy generation. At the macroscopic level, a thermodynamic characterization model of logistics network topology and a global exergy balance equation have been established, enabling accurate identification of key scales and nodes responsible for system energy degradation. At the optimization level, a dual-layer iterative optimization framework integrating the physical layer and the logistics layer has been developed, in which global entropy generation minimization is adopted as the core objective, thereby overcoming the limitations of conventional optimization targets. In addition, a coordinated regulation mechanism based on exergy loss decoupling and virtual exergy pricing has been proposed, enabling closed-loop coordination between the physical and control layers and effectively resolving cross-scale coupling inconsistencies in optimization.

Comprehensive validation through multi-scenario simulations and real-vehicle experiments confirms the effectiveness and reliability of the proposed framework. At the microscopic level, prediction errors under representative transient operating conditions are consistently controlled within 5%, demonstrating a clear improvement over conventional steady-state models. At the mesoscopic–macroscopic level, the coupling model accurately quantifies congestion-induced entropy and its amplification effect on entropy generation across different traffic states, with coupling errors maintained below 3%. At the system level, the proposed optimization strategy achieves substantial performance gains compared with conventional shortest-distance and shortest-time approaches, including energy consumption reductions of 15.3%–20.4%, exergy efficiency improvements of 10.3%–12.8%, and reductions in global entropy generation of 27.9%–33.4%, while maintaining a high level of on-time delivery performance and economic efficiency. Sensitivity analysis further demonstrates that the proposed model and optimization mechanism exhibit strong adaptability across diverse urban forms and distribution modes.

The findings provide significant theoretical and engineering contributions. The application scope of nonequilibrium thermodynamics in complex engineering systems is expanded, and the theoretical framework of multiscale entropy generation coupling in complex networked systems is further developed. In addition, the transition of exergy analysis from theoretical investigation to practical engineering application is advanced, and a thermodynamic first-principles foundation is established for improving energy efficiency in urban logistics systems. Furthermore, the limitations of conventional urban logistics optimization approaches—characterized by an overemphasis on geometric and temporal factors and insufficient consideration of physical mechanisms—are effectively overcome. Key technical challenges, including cross-scale coupling inconsistency, difficulty in identifying dominant dissipation sources, and the restriction to single-objective optimization, are addressed. Overall, a feasible theoretical and technological pathway is provided for promoting green and low-carbon development in urban logistics systems. At the same time, a generalizable modeling and optimization paradigm is established for energy efficiency improvement in analogous complex engineering systems.

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