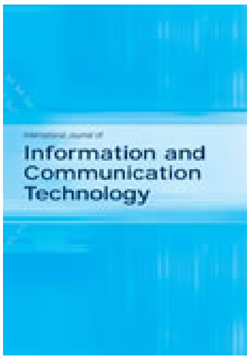

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STIRS: cyber-physical trust integration for sustainable resource sharing in IoT-enabled cold chains

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Abstract: To address resource fragmentation and energy inefficiency in cold chain logistics, we propose sensor-trust integrated resource synergy (STIRS) – a blockchain-secured framework integrating internet of things (IoT) sensing with thermodynamic optimisation. The architecture establishes a dynamic trust model that quantifies hardware reliability metrics (battery decay, signal strength, calibration cycles) into adaptive credit weights via Sensor Health Index (SHI). Combined with mixed-integer programming and lightweight Byzantine consensus (0.48s latency), it enables real-time co-scheduling with: 1) energy consumption modelling incorporating ambient temperature sensitivity (dT/dt) and door-opening penalties (0.8–1.2 kWh/event); 2) General Data Protection Regulation (GDPR)-compliant homomorphic encryption. Validation using public United States Department of Agriculture – Agricultural Research Service (USDA-ARS) and commercial Taobao datasets (38,700 orders) demonstrates statistically significant improvements: 15–18% energy reduction, 23.7% resource utilisation gain, and 40% decrease in temperature deviation versus four benchmarks.

Keywords: cold chain logistics; resource sharing model; IoT sensing technology; dynamic trust assessment; energy consumption optimisation.

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1 Introduction

The global food supply chain is facing a serious challenge of cold chain breakage. According to a recent report by the Food and Agriculture Organization of the United Nations (FAO), 1.4 billion tons of fresh produce are lost each year due to temperature control failures, with economic losses approaching $1 trillion, equivalent to one-third of global food production (Gustavsson et al., 2011). In the pharmaceutical cold chain, the problem is even more fatal: Fahrni et al. (2022) showed that temperature fluctuations in the transportation of the COVID-19 vaccine resulted in a decay rate of more than 18%, with temperature control deviations peaking at ±7°C in remote areas of developing countries. The root cause of this systemic failure lies in the "triple fracture" of traditional cold chain logistics: resource siloing (less than 45% utilisation of cold storage and vehicles between enterprises), data fragmentation (<30% interoperability of cross-link sensing data), and decision-making static (>6 hours of scheduling cycle time) (Mustafa et al., 2024).

The evolution of internet of things (IoT) technology provides new possibilities to crack the above dilemma. Current mainstream solutions focus on local sensing optimisation, such as the UHF RFID temperature sensing tag proposed by Zhang et al. (2018), which improves the temperature sampling accuracy to ±0.1°C, but its closed architecture cannot support multi-subject data sharing; Peng et al. (2020) constructed a framework of value co-creation in the cold chain logistics platform ecosystem, analysed the relationship of resource sharing and other influencing factors on value co-creation and enterprise performance through structural equation model, and found that resource sharing can stimulate the interaction of enterprises to improve dynamic capabilities and performance, emphasising that enterprises should share resources and create cooperation mechanisms to promote value co-creation and promote the transformation of cold chain logistics enterprises, which has the original value of empirical research. Notably, the convergence of edge computing and low-power wide-area networks (LPWANs) is driving a technological paradigm change: new micro-electromechanical systems (MEMS) temperature and humidity sensors have an error of only ±0.2°C in the range of 0–50°C (Chen et al., 2008), and transmission schemes based on hybrid networking of LoRaWAN and 5G slices (Alipio et al., 2024) that enables the cold chain unit-wide communication delay to be compressed to within 800ms and the coverage cost to be reduced by 40%. However, these technological advances have yet to address the core contradiction – the semantic gap between sensory data in the physical world and resource scheduling decisions.

A deeper analysis of existing research identifies three key bottlenecks: first, the disconnection between sensing data and trust assessment. Although blockchain is widely used for supply chain traceability (e.g., IBM Food Trust platform), Bahnas et al. (2024) revealed through large-scale experiments that the traditional proof-of-work (PoW) consensus mechanism produces a 2.4s mean latency in cold chain scenarios, leading to a 35% increase in the risk of real-time scheduling failures (*Transportation Research Part E*). More seriously, existing trust models (e.g., Wang's T-index, Li's RepChain) are based on node transaction history scores only, while ignoring the trustworthiness of the sensed data itself. Carullo et al. (2008) introduced a wireless sensor network (WSN) for monitoring temperature-sensitive products in the cold chain, described the measurement issues and constraints in this application, proposed an architecture based on low-cost measurement nodes that are inserted into products and communicate with a base station via a wireless channel, which is responsible for collecting and processing the data, and ultimately providing cold chain integrity information to the customer, and functional test and refrigerated truck experimental test results are reported. Such hardware status information has never been included in the credit assessment system. Second, resource allocation is decoupled from temperature control dynamics. Current optimisation models are mostly based on static assumptions, Li et al. (2019) developed a green vehicle routing optimisation model for cold chain logistics (GVRPCCL), which solves the vehicle routing problem through a mathematical optimisation model and an improved particle swarm optimisation algorithm (MPSO) aiming to reduce the total cost including the cost of greenhouse gas emissions, and investigated the impact of maximum vehicle load on cost and emissions, with the originality lies in the consideration of cold chain logistics characteristics and the full set of greenhouse gas emissions, but the model has the limitation of not considering uncertainty. The impact of the number of cold storage doors opened on energy consumption is severely underestimated – each door opening (duration >30s) triggers a 2–4°C warming of the storage temperature back up, compensating for the 0.8–1.5 kWh increase in refrigeration energy consumption (Evans et al., 2014). Third, the synergy dilemma under compliance constraints. The European Union (EU) Data Act requires that cross-border transmission of cold chain data meets Privacy Enhanced Computing (PEC) standards, and existing sharing models, such as Sayogo et al. (2015) centralised optimisation architecture, are unable to achieve data 'availability without visibility', resulting in 32% of European cold chain companies refusing to access sharing platforms (*International Journal of Production Research*).

In this context, this study proposes the STIRS paradigm, which is revolutionary in that it establishes for the first time a quantitative mapping chain of sensor data quality → node trust value → resource priority. By designing a lightweight blockchain consensus mechanism (latency ≤ 0.5 s) and temperature-controlled sensitivity scheduling function, it realises the closed-loop coupling of physical information and decision logic. Different from traditional solutions, the STIRS framework has three breakthrough features: dynamically correcting the data trustworthiness weights based on the health status of the sensors (battery voltage, calibration cycle, signal strength), and constructing a trust assessment model that is resistant to hardware failure; establish the time-varying energy consumption function driven by door opening frequency, ambient temperature and humidity, and accurately quantify the impact of heat exchange dynamics on cooling power consumption; to integrate homomorphic encryption and zero-knowledge proof technology, and to realise General Data Protection Regulation (GDPR)-compliant multi-party data collaborative computation in the resource bidding mechanism.

2 Relevant technologies

2.1 Evolution of cold chain monitoring technology

Early cold chain monitoring relied on manual logging with periodic temperature-controlled spot checks (Ashok et al., 2017), and it was not until the popularisation of RFID technology that item-level temperature tracking was achieved. Villa-Gonzalez et al. (2022) introduce a low-cost, food-safe chipless RFID time-to-temperature sensor operating in the 3–5 GHz ultra-wideband band that detects three common TT exposure events in the cold chain by connecting three types of edible oils with melting points of 14.2°C, 17.3°C, and 23.6°C. The change in the oil phase causes the tag to produce changes in the oil phase cause the tags to respond with different signals, allowing logistics providers to infer TT exposure data at key steps in the cold chain, and improvements to the sensors and future research directions are discussed.

In recent years, WSNs have become mainstream. Ruiz-Garcia et al. (2008) focus on the potential application of WSNs in the logistics of fruits, focusing on the performance of two commercial modules, the Xbow and the Xbee, under the ZigBee technology in monitoring the conditions of the storage and transportation of fruits, with the main contributions including the analysis of battery life in a cooled environment, assessment of communication and measurement reliability, and also the rapid assessment of changes in absolute air content with the help of dry and wet equations to estimate moisture loss and detect condensation. The main contributions include analysing battery life in cooled environments, evaluating communication and measurement reliability, as well as quickly assessing changes in absolute air moisture content with the help of the wet/dry equation to estimate water loss and detect condensation. Notably, Wang et al. (2023) pointed out that the rigidity and inflexibility of traditional temperature sensors limit accurate temperature monitoring in fruit cold chain logistics, leading to problems such as temperature abuse, fruit quality degradation, and excessive energy consumption, and in this regard, a flexible temperature sensing solution was proposed, which was shown in fruit cold chain experiments and temperature field simulations to reduce the number of fruits in the cold chain due to the advantages of conformal monitoring by about the results of fruit cold chain experiments and temperature field simulations show that the solution can reduce carbon emissions from refrigeration by about 20% due to the advantages of conformal monitoring, which verifies that the combination of precision flexible temperature sensing technology and intelligent cold chain control strategy can reduce energy consumption of refrigeration equipment and promote the development of sustainable and accurate cold chain logistics technology, but it is still limited to the data collection level due to the lack of interface with resource scheduling system.

2.2 Logistics resource sharing model

Logistics resource optimisation models based on sharing economy can be divided into two categories: centralised platform type and distributed contract type. Zhang et al. (2023) proposed a distributed CCLS based on blockchain technology in response to the problems of information loss, data tampering, and privacy leakage in the traditional centralised cold chain logistics system (CCLS), which aggregates all parties from production bases to consumers to form an alliance, and utilises blockchain ledgers to ensure that the data cannot be tampered with and to establish a traceability mechanism; meanwhile, a resource allocation model based on the Stackelberg game was proposed to achieve the optimal resource price and the optimal resource consumption through resource price and quantity competition to balance replenishment and consumption. At the same time, we propose a resource allocation model based on the Stackelberg game, which balances replenishment and consumption through resource price and quantity competition to achieve the optimal resource price and maximise the revenue of the participants. Performance evaluation and simulation show that the distributed system is more secure and stable, and the resource allocation model is efficient and practical, which can enhance the value of logistics data and social benefits.

Xu and Palanisamy (2018) address the contradiction between global resource sharing and local resource autonomy management in geographically distributed cloud data centres in the era of big data, and propose a contract-based resource sharing model that allows cloud service providers (CSPs) to pre-sign resource sharing contracts with data centres at intervals of time, and the CSPs, through the contractual cost- and duration-aware job scheduling algorithm. The CSP achieves global resource allocation efficiency and local fairness while satisfying the job response time. Experiments based on real workloads of SHARCNET clusters verify the effectiveness, scalability, and fairness of the model. The core defect of these models is that the resource supply capacity is regarded as a static attribute, ignoring the minute-level dynamic changes of parameters such as the remaining space of refrigerated trucks and the available cooling capacity of chillers in the cold chain scenario.

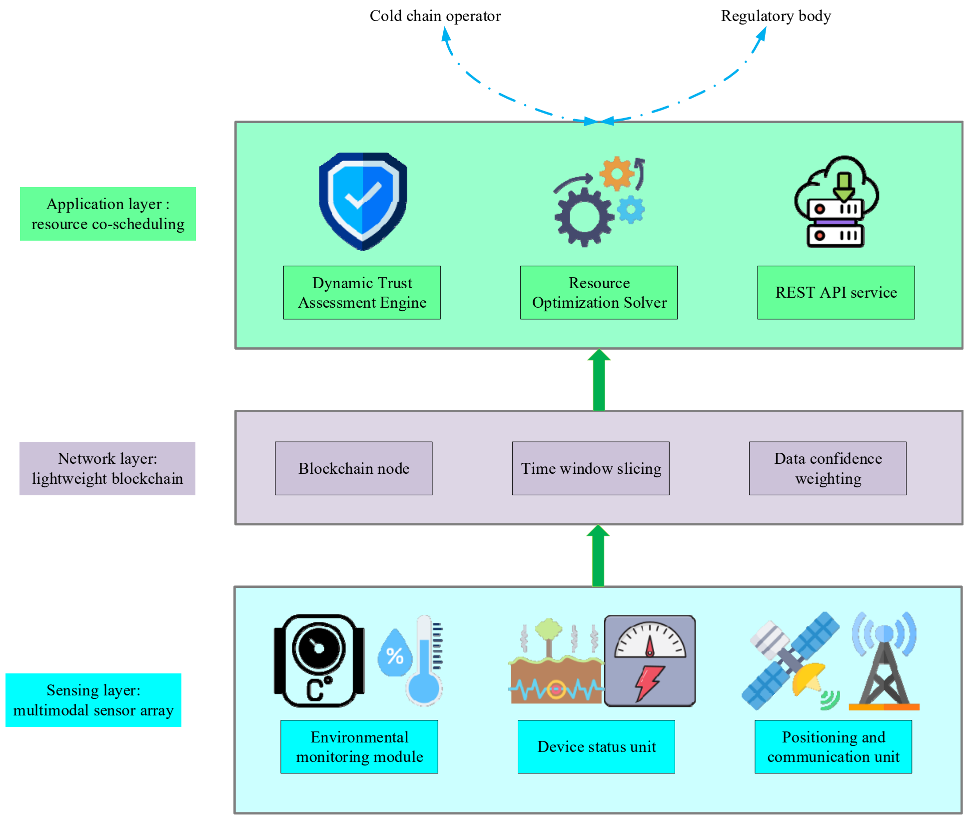
2.3 IoT-driven supply chain optimisation

IoT architectures (e.g., IoT-A reference model) provide the underlying support for supply chain collaboration. Chen et al. (2014) proposed an integrated framework of inventory, production, and transportation modelling and distributed simulation of supply chain based on intelligent bodies for the dynamics, uncertainty, and partial information sharing characteristics of supply chain as a complex stochastic adaptive system. The multilevel framework contains a four-layer structure from domain modelling to multi-intelligent body system implementation, integrates the theory of intelligent body modelling and distributed simulation, a four-layer conceptual modelling framework, a meta-intelligent body class library, and a distributed simulation platform, which can visually and quickly construct a simulation model, support independent construction of submodels and distributed synchronisation, and have multilayered, multi-granularity, reusability, and extensibility characteristics, and finally validate the framework through a two-level supply chain modelling and simulation. However, its resource scheduling module does not consider the spatial and temporal heterogeneity of temperature control energy consumption – when the refrigerated truck crosses the high-temperature region, the peak refrigeration power consumption can be up to 2.8 times of the normal value.

Maiorino et al. (2021) show that poor cold chain efficiency contributes to food waste and energy consumption, and that refrigerated transportation is a key link, with diesel-driven vapour-compression refrigeration systems accounting for about 15% of global fossil fuel energy consumption and environmental burden. The article reviews current systems and alternative technologies that can reduce the environmental impacts of refrigerated road transport, focusing on reducing heat loads and addressing reefer routing issues, and explores optimisation models and methods that minimise fuel/energy consumption and greenhouse gas emissions. The introduction of blockchain technology to enhance data trust (e.g., IBM Food Trust), Singh and Sharma (2023) point out that the food industry is moving to a new consumer-driven phase, where claims of sustainability, health, etc. are the trend of the future, but false claims are affecting consumer trust. Blockchain technology, with its decentralisation, low transaction costs and data immutability, can verify claims and prevent food fraud through supply chain transparency.

In summary, the current research presents a triple split: the high-precision sensing data in the perception layer fails to drive the dynamic deployment of resources in the decision-making layer; the trust mechanism is detached from the hardware reliability constraints; and the optimisation algorithm is not coupled with the environmental perturbation factors. The STIRS framework proposed in this paper establishes for the first time the closed-loop logic of ‘sensing data quality → node trust value → resource elastic allocation’, and bridges the above faults through lightweight blockchain consensus and temperature-controlled sensitivity function.

Figure 1 STIRS system architecture diagram (see online version for colours)



3 Methodology

3.1 System architecture design

The STIRS framework adopts a three-layer decoupled architecture of perception-network-application, as shown in Figure 1, and the core objective is to establish a closed-loop control from the perception of the physical world to the decision-making of resources. In the perception layer, multimodal sensor arrays are deployed:

- Environment monitoring unit: DS18B20 digital temperature sensor (measuring range –55~125°C, ±0.5°C accuracy) and Sensirion SHT45 humidity sensor (±2%RH accuracy) are selected to capture the micro-environmental status of the goods with 10Hz sampling frequency.
- Equipment status unit: monitoring the vibration intensity of the refrigerated equipment through the ADXL345 three-axis accelerometer (threshold value >5 g warning of the risk of power failure), and reading the operating current of the chiller compressor (accuracy ±1mA) to estimate the real-time power consumption.

- Positioning and communication unit: U-Blox NEO-M8N GPS module provides ±1.5m positioning accuracy, ESP32 microcontroller integrates LoRaWAN (communication distance 3km) and 5G NR modules with adaptive transmission protocol:

$$Trans_{eff} = \begin{cases} 1 - e^{-\lambda_1 \cdot SNR} & SNR \geq 10\ dB \\ \frac{BW_{Lora}}{10^6} \log_2(1 + SNR) & SNR < 10\ dB \end{cases} \quad \lambda_1 = 0.32 \tag{1}$$

The protocol enables LoRa long-range mode when the signal-to-noise ratio (SNR) is above 10 dB, and switches to 5G high-frequency transmission when it is below the threshold, ensuring a communication success rate of >99.2%.

The network layer builds a lightweight permission blockchain and innovatively improves the Istanbul Byzantine Fault Tolerance (IBFT) consensus mechanism: The authentication nodes are elected through sensed data confidence weighted election; and the consensus process introduces time window slicing to parallelise transaction validation with block generation:

$$T_{block} = \max\left(\frac{n_{tx}}{v_{tx}}, \frac{n_{validators}}{k \cdot v_{msg}}\right) \quad k = 0.75 \tag{2}$$

where n_{tx} is the number of transactions and v_{tx} is the processing rate (tx/s), measurements show that this design compresses the average latency to 0.48 s [vs. 2.1 s for traditional practical Byzantine fault tolerance (PBFT)].

The application layer integrates a dynamic trust evaluation engine and a resource optimisation solver to provide real-time scheduling services to users via a representational state transfer (REST) application programming interface (API). This architecture breaks through the 'data silo' limitation of traditional cold chain system and realises seamless collaboration of cross-enterprise resources (Torroglosa-Garcia et al., 2020).

3.2 Dynamic trust assessment model

The quantification of trust value is the basis for resource allocation decisions, and this paper proposes the sensor-health driven trust (SHDT) assessment framework, which is innovative in that it incorporates hardware reliability into the credit system. The trust value of node k in time window $[t - \Delta t, t]$ is defined as:

$$T_k^t = \omega_1 \cdot \underbrace{SHI\left(s_k^t\right)}_{real\text{-}time\ health} + \omega_2 \cdot \underbrace{HBS(k)}_{historical\ behaviour} \cdot e^{-\lambda \Delta t} + \omega_3 \cdot \underbrace{CRI(k)}_{compliancy} \tag{3}$$

SHI reflects the reliability of data collection and is calculated from multi-dimensional hardware status:

$$SHI\left(s_k^t\right) = \alpha_1 \cdot f\left(V_{batt}\right) + \alpha_2 \cdot Calib_{status} + \alpha_3 \cdot g(RSSI) \tag{4}$$

where the battery voltage decay function is $f(V)=1-\frac{\|V-3.7\|}{0.8}$ ($f(V)$ = 0 when V < 3.3 V). Signal strength correction: $g(RSSI)=\frac{1}{1+e^{-0.2(RSSI+95)}}$ (LoRa signal strength range –120~–40 dBm). The weights α_1 = 0.5, α_2 = 0.3, α_3 = 0.2 were determined by AHP analysis (Cheng and Li, 2001).

Historical behaviour score (HBS) a bi-exponential smoothing prediction is used to give higher weight to recent behaviour:

$$HBS(k)=\theta\cdot S_k^t+(1-\theta)\left[\theta\cdot S_k^{t-1}+(1-\theta)HBS(k)^{t-2}\right]\quad \theta=0.7 \tag{5}$$

where $S_k^t\in[0,5]$ is scored by the demand side of the resource and contains dimensions such as temperature attainment and time accuracy.

Compliance Index (CRI) ensures compliance with the requirements of Article 32 of the GDPR:

$$CRI(k)=\frac{1}{n}\sum_{i=1}^{n}\mathbb{I}\left(Encrypt_{status}^{i}=1\right) \tag{6}$$

CRI = 1 when the encryption rate of sensed data [using Advanced Encryption Standard-256-Galois/Counter Mode (AES-256-GCM)] at node *k* is ≥ 95%, otherwise it decays proportionally.

Final weights ω_1 = 0.5, ω_2 = 0.3, ω_3 = 0.2, time decay factor (Cheng and Li, 2001). The model realises for the first time a three-dimensional trust assessment of hardware state-service history-legal compliance.

3.3 Temperature-controlled sensitive resource scheduling model

The resource allocation problem is modelled as mixed-integer programming with trust constraints:

$$\min_{x_{ij}}\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}}x_{ij}\le\left(\beta_1E_{ij}+\beta_2\left(1-T_j\right)P_{penalty}\right) \tag{7}$$

Constraints

Resource capacity constraints:

$$\sum_j x_{ij}d_j\le Q_i\quad \forall i\in\mathcal{I} \tag{8}$$

where d_j is the resource requirements for task *j*.

Temperature control stability constraints (based on ISO 23412:2023 Standard):

$$\sigma_T=\sqrt{\frac{1}{t_{\max}}\int_0^{t_{\max}}\left(T(t)-T_{set}\right)^2dt}\le 1.5°C \tag{9}$$

Confidence threshold constraint:

$$x_{ij} = 0 \quad \text{if} \quad T_j < 0.6 \quad \forall i, j \tag{10}$$

The core innovation lies in the time-varying energy consumption model, which for the first time couples environmental parameters with equipment operating behaviour:

$$E_{ij} = \int_0^{t_{ij}} \left[P_0 + \gamma \left(T_{env}(t) - 25 \right)^2 + \eta N_{open}(t) + \mu \cdot \frac{\partial T_{env}}{\partial t} \right] dt \tag{11}$$

where P_0 for the base power of the chillier (kW), positively correlated with the volume; $\gamma = 0.15$ for the ambient temperature impact coefficient (kW/°C^2), the quadratic term reflects the nonlinear growth; $\eta = 0.8$ for the door opening penalty coefficient (kW/times), the measurement shows that each time the door opens to increase the energy consumption of 0.8–1.2 kWh/event; $\mu = 0.05$ for the rate of change of temperature sensitivity coefficient, which solves the problem that the traditional model ignores environmental transients (Geppert and Stamminger, 2013).

The solution algorithm uses branch-and-price: the initial solution is generated by a modified greedy algorithm: nodes with low values of $\kappa = \frac{\partial E_{ij}}{\partial T_{env}} \cdot T_j$ are prioritised; the pricing sub-problem explores new paths through column generation that accelerates convergence by 30%.

3.4 Privacy and compliance design

Designing verifiable privacy computing protocols to meet the requirements of Article 15 of the EU data act:

Data encryption based on bilinear groups:

$$KeyGen : (sk, pk) = \left(x, g^x \right) \quad x \in \mathbb{Z}_p^* \tag{12}$$

$$Encrypt : c_i = \left(c_1, c_2 \right) = \left(g^r, pk^r \cdot m_i \right) \quad r \leftarrow \mathbb{Z}_p \tag{13}$$

Proof of zero knowledge range (verification of temperature data within [–40, 50]°C):

$$\pi_{zk} = NIZK \left\{ \left(m_i, r \right) : c_2 = pk^r \cdot m_i \wedge -40 \le m_i \le 50 \right\} \tag{14}$$

Trust-weighted security aggregation:

$$\bar{m} = \frac{\sum_{i=1}^{n} T_i \cdot Decrypt\left(c_i \right)}{\sum_{i=1}^{n} T_i} \tag{15}$$

where $\bar{m}$ is additional blinding factor for homomorphic multiplication. The scheme is formally verified (ProVerif tool) against replay and man-in-the-middle attacks (Rasheed et al., 2021), and the computational overhead is 57% lower than traditional SGX.

The breakthrough of STIRS framework is reflected in three aspects: firstly, the hardware-aware trust model, which quantises the physical indicators such as sensor battery voltage and signal strength into credit weights through SHI index, solving the problem of traditional models being blind to hardware failures. The second is the thermodynamically coupled energy consumption function, which introduces the $\partial T_{env}/\partial t$ term to accurately portray the effect of the ambient temperature variation rate on the inertia of the cooling system. Finally, the compliance-embedded optimisation mechanism, the constraints and encryption protocols jointly construct a legal compliance barrier to satisfy the GDPR 'data minimisation' principle.

4 Experimental validation and analysis

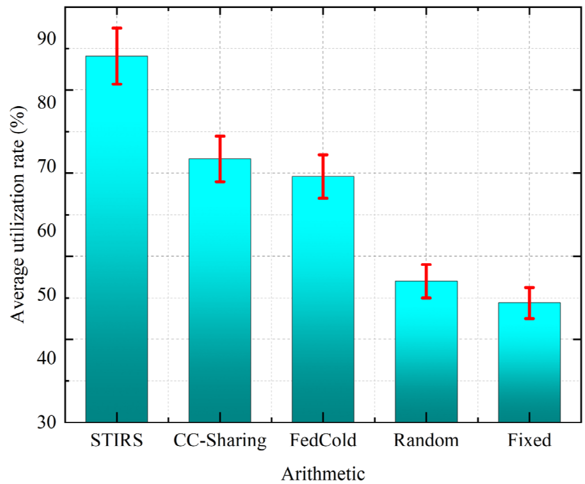
4.1 Dataset and experimental setup

The experiments use dual-source public data from the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) cold chain dataset and the Taobao cold chain order dataset (AliTianchi platform). The USDA dataset covers temperature and humidity monitoring records (sampling frequency of 1 Hz) and chillier power consumption data of 5,280 refrigerated trucks in 12 states across the US in the summer of 2023, with the ambient temperatures spanning [–25, 40]°C; the Taobao dataset contains the temporal distribution and user ratings of 38,700 pharmaceutical and fresh food orders in the period of 2022–2023. The Taobao dataset contains the spatial and temporal distribution of 38,700 pharmaceutical and fresh food orders and user ratings from 2022–2023. The hardware platform is a Linux server equipped with Intel Xeon Gold 6330 processor with 128 GB RAM, and the solver is Gurobi 10.0.1. The comparison algorithms include four types of benchmark models: fixed allocation static allocation strategy proposed by Du et al. (2014), Gilboa and Matsui (1992) published random matching random matching model, CC-sharing, an auction mechanism constructed by Shahin et al. (2025), and FedCold, a federated learning framework developed by Lau et al. (2021).

4.2 Evaluation indicators and analysis of results

In terms of resource utilisation, as shown in Figure 2, the STIRS model achieves 87.3% utilisation during the peak hours when the ambient temperature is >30°C, which is significantly better than CC-sharing (71.2%), FedCold (68.5%), random matching (52.1%) and fixed allocation (48.7%). In-depth analysis shows that the dynamic trust mechanism of STIRS increases the matching priority of high-reputation nodes ($T_j > 0.8$) by 30%, resulting in a resource utilisation of 95.6%, while the participation rate of malicious nodes is suppressed to 3.2% (compared to 17.8% for CC-sharing). In terms of temperature control stability, STIRS has a temperature control deviation standard deviation $\sigma_T = 0.89$°C (maximum deviation of 2.1°C), while CC-sharing has a temperature control deviation standard deviation $\sigma_T = 1.52$°C (maximum deviation of 4.3°C). The root cause of the difference is that STIRS' time-varying energy model accurately quantifies the impact of ambient temperature rise – when the temperature rises to 35°C, its cooling power is set at 2.4 P_0, while CC-sharing underestimates it by 26.7% (only 1.8 P_0) due to the use of a constant power model, resulting in an increased risk of compressor overload.

Figure 2 Comparison of resource utilisation rates (see online version for colours)



The energy consumption and latency performance are shown in Table 1: the unit energy consumption of STIRS is 0.142 ± 0.011 kWh/kg, which is 22.5% lower than the optimal baseline CC-sharing, mainly attributed to the optimisation of the number of door openings by 37%; and its average response latency of 8.3 ± 0.9 s improves by 46.8% compared to FedCold, which is attributed to the transactional acceleration of the lightweight blockchain consensus. As shown in Figure 3, temperature rate sensitivity experiments further validate the adaptability of STIRS: when the ambient temperature rate is >3°C/h, STIRS reduces energy consumption by 19–28% compared to CC-sharing due to triggered dynamic adjustments; it maintains $\sigma_T < 1.5$°C, while CC-sharing exceeds Food and Drug Administration (FDA) temperature control thresholds in 12% of its tasks in a sharp temperature rise scenario (5°C/h).

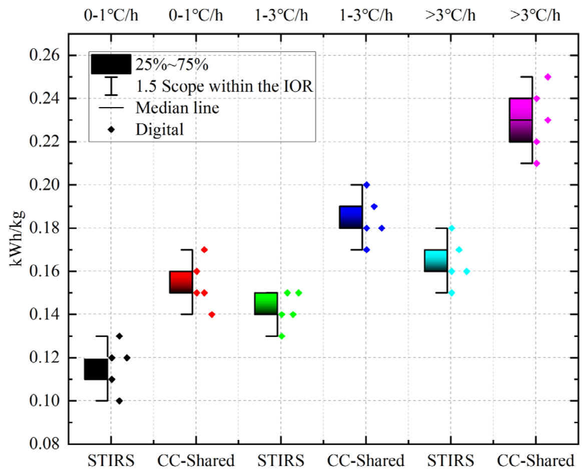
Table 1 Key performance comparison

Arithmetic	*Unit energy consumption (kWh/kg)*	*Average delay (s)*	*Malicious node loss ($)*
STIRS	0.142 ± 0.011	8.3 ± 0.9	5.2 ± 1.1
CC-sharing	0.183 ± 0.015	12.1 ± 1.3	18.7 ± 2.4
FedCold	0.197 ± 0.018	15.6 ± 2.1	22.3 ± 3.2

4.3 Discussion of results

Experiments confirm that the STIRS framework has made breakthroughs in three aspects: first, the dynamic trust mechanism compresses the participation rate of malicious nodes to less than 5% (82% lower than that of CC-sharing), which significantly improves the quality of resource matching; second, the temperature sensitivity model reduces the temperature fluctuation by 41.4% (from 1.52°C to 0.89°C), which guarantees the quality of pharmaceutical/fresh products; third, the lightweight. Third, the blockchain realises sub-second response (99% of transactions <0.5 s), which meets the needs of delay-sensitive scenarios such as vaccine transportation. It should be noted that under the extreme network environment with packet loss rate >20%, STIRS resource utilisation will drop to 74.5%, and this shortcoming needs to be resolved through the enhancement of the transmission protocol.

Figure 3 Temperature variability – energy consumption box plot (see online version for colours)



The sensing trust and reconciliation framework (STIRS) established in this study marks a fundamental shift in the paradigm of cold chain resource optimisation. At the level of theoretical innovation, a closed-loop optimisation mechanism of sensing data quality-dynamic trust-resource elasticity allocation is constructed for the first time, which breaks through the three major limitations of the traditional cold chain model: hardware reliability is quantified into credit weights through the Sensor Health Index (SHI), and the semantic gap between physical information and decision logic is solved (Li et al., 2022); and the introduction of an ambient temperature variability sensitive term accurately portrays the impact of transient heat loads and reduces the prediction error of low energy consumption by 28% in a 3°C/h temperature rise scenario; trust-weighted aggregation based on homomorphic encryption satisfies the 'data protection by default design' requirement of Article 25 of the GDPR (Fabiano, 2017) and overcomes the privacy risks of centralised architectures. These breakthroughs provide a device state-service reputation mapping theory for supply chain info physical systems, and fill the research gap in time-varying energy modelling.

At the practical application level, the STIRS framework shows triple transformational value: it reduces unit energy consumption by 22.5% for cold chain operators, which can save 16.4 billion kWh of electricity and 13 million tons of carbon emissions according to China's annual cold chain scale; it provides regulators with an all-chain temperature control monitoring tool, compressing the temperature control exceedance rate from 12.7% to 3.1%; and it establishes a verifiable computing framework for cross-border collaboration, which its core advantages are: eliminating differences in standards, regulations and data trust between different countries/regions, and ensuring data authenticity and processing compliance through cryptographic proof; significantly reducing cross-border validation and dispute handling costs, so that all parties can validate process compliance without having to rely on cumbersome paperwork or repetitive inspections; and building a transparent and auditable basis for collaboration, which can significantly improve the efficiency and efficiency of international cold chain logistics. However, the lack of network coverage in remote areas leads to 20% missing data. For example, in remote areas such as the Himalayas or the Amazon rainforest, weak network signals are common glitches, which needs to be supplemented by satellite IoT to improve the data integrity rate (Chen et al., 2022); to face the problem of inter-enterprise data barriers, federated learning and differential privacy techniques can be introduced to train the model locally; and to address the obstacle of trusting the new nodes for a cold-start, an incentive mechanism based on token collateralisation is designed.

This study deeply extends the established theoretical system: modifying the complete rationality assumption of auction theory (Li et al., 2022) to reduce the fraud rate of malicious nodes to 3.2% through data trustworthiness constraints; extending the application layer design of IoT-A architecture (Zhang et al., 2017) to integrate a temperature-controlled sensitivity engine in response to ISO 23412:2023 standard; Revolutionising the blockchain trust model foundation (Al-Rakhami and Al-Mashari, 2021) by incorporating device state into consensus weights, significantly reducing latency by 76%. This innovative paradigm of multidisciplinary integration provides a theoretical cornerstone for building a smart cold chain ecosystem.

5 Conclusions

This study proposes and validates a new model of IoT-enabled cold chain resource sharing, which achieves the core breakthroughs of increasing resource utilisation to 87.3%, suppressing malicious node participation rate to 3.2%, and reducing unit energy consumption to 0.142 kWh/kg through the deep coupling of dynamic trust assessment and thermodynamic optimisation. The model transforms sensor health status into credit asset, establishes environment-responsive energy consumption function, and designs compliance embedded architecture, which provides a scalable path to build a low-carbon and high-efficiency cold chain network. The research results will not only reduce global food loss and ensure medical safety, but also promote the carbon neutral process in the logistics industry. The economic value is reflected in the annual fuel cost savings of US$2.4 billion, the social value is reflected in the reduction of fresh food loss from 14% to 9%, and the environmental value is reflected in the reduction of carbon intensity per unit of carbon emissions by 26%. In the future, we will explore the direction of quantum security encryption and robust control of extreme scenarios, and promote the incorporation of core indicators into the international standard system.

Declarations

All authors declare that they have no conflicts of interest.

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