Design of Cold Chain Logistics Layouts Leveraging Phase Change Material Technology: A Case Study in the Yangtze River Delta Region

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Abstract. Under traditional technical conditions, the cold chain (warehousing, transportation, and retail) model is becoming increasingly mature, and the market is becoming saturated. Industry development has many pain points, and technological innovation is always the biggest driving force for breakthroughs. There are practical applications of phase change materials in cold chain logistics in China. The material has the advantages of stable temperature maintenance, is non-toxic and harmless, and can achieve cold storage refrigeration during transportation, reducing carbon emissions. In the case of overcoming technical difficulties, how to widely apply it in the field of cold chain logistics requires a reliable model to support it. This research will be based on the specific practice of existing applications of phase change materials in Jiangsu Province, taking the Yangtze River Delta region as an example, analyzing the advanced cold chain logistics network layout of existing super-large cities, and providing market access to advanced technologies for global urban agglomerations. and regional model layout ideas.

1 Introduction

Cold chain logistics refers to a systematic project that uses refrigeration technology to continuously maintain a suitable temperature and humidity environment for perishable products such as fruits, vegetables, and medicines during the production, storage, transportation, sales, and consumption processes to ensure product quality [1, 2]. During the circulation process, due to various external factors such as technical reasons and the irregular behavior of the practitioners themselves, the products are exposed to normal or high-temperature environments, resulting in spoilage and deterioration, often called “chain-breaking” [3]. Although China's cold chain logistics is gradually recovering after the epidemic, it is expected to generate US$80 billion in revenue in 2024 [4]. However, “chain breaking” caused by widespread practical problems such as insufficient infrastructure, uneven distribution of resources, high transportation costs, and significant energy consumption is still hindering the development of the industry, bringing food safety risks, waste of food resources and other major hidden dangers [5]. In addition to further

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standardizing industry behavior, continuously stimulating demand, and providing policy support, technological innovation is bound to be one of the important driving forces for industry breakthroughs [6].

As a latent heat energy storage material, phase change materials (PCMs) can release stored cold energy at higher temperatures, thus enabling energy transfer across space and time [7]. PCMs possess high energy storage density, extended temperature control duration, stable chemical properties, and are non-toxic and non-flammable, which has garnered significant research interest and attention in logistics [8]. Unlike the widely used mechanical refrigeration technology, PCMs integrate their excellent properties with traditional cold chain logistics models. In addition to reducing process costs, extending freshness periods, and enhancing food safety, they also facilitate a passive low-temperature operation mode that yields the additional benefits of reducing carbon emissions and promoting green development. PCMs are available in various classifications to meet the application needs of different scenarios, indicating their broad development prospects within the industry. In Nanjing, cold storage containers utilizing PCM technology have been implemented in actual operations. Additionally, Shenzhen Bao'an International Airport and Tokyo Haneda Airport in Japan have collaborated with relevant companies to develop PCM thermal cold storage projects.

PCM, as a new cold chain logistics preservation technology, has attracted the attention of many researchers due to its superior performance and broad application prospects. Existing research has achieved specific results in the characteristics and applications of PCM materials, such as the experimental effects of different types of PCM materials on the preservation of other products [9]. And the model scheme of using PCM technology to transform traditional refrigerated trucks [10]. The technical level and implementation threshold are no longer major obstacles. However, a single research and application model makes it challenging to promote the further development of technology. How to use interdisciplinary thinking to apply PCM technology to actual scenarios and conduct regional layouts based on urban development needs is a direction worthy of in-depth study.

This study takes Jiangsu Province as an example, focuses on the practical application of PCM technology in cold chain logistics, combines the radiation theory of urban cold chain logistics networks, and conducts an in-depth analysis of the regional model layout of key cities, aiming to provide a reliable cold chain for large urban agglomerations—regional facility layout plan. The research will be based on actual cases to explore the path for the large-scale promotion of PCM technology applications and provide assistance with its practical operation.

2 Case selection and background

Based on background significance and industry literature research, this study pays special attention to the typicality, originality, and popularization of the selected cases to ensure they are significant to cold chain logistics among existing phase change materials.

The selected company relies on a large-scale agricultural and sideline products trading platform in Nanjing. It has an in-depth understanding of traditional and emerging cold chain logistics models (such as fresh food e-commerce, etc.) to decide to invest in a scientific and technological achievement transformation project that recycles phase change cold storage materials into cold chain containers. The initiative aims to solve problems such as the low cold treatment rate of agricultural products, insufficient field pre-cooling and cold storage, reduced transportation costs due to seasonal harvests, and spoilage and food safety, with special attention to the "first-mile" circulation part.

The company has successfully developed and applied for a patent and launched a new type of cold storage phase change material container. Different from traditional mechanical refrigeration containers, this new type of container can stay refrigerated for 3-7 days after

charging for 1-2 hours. By intelligently utilizing valley power to save electricity costs, this technology achieves more than 70% of energy savings. At the same time, relying on sensors and information technology, containers' cooling filling and feedback monitoring are realized, improving the efficiency and availability control during transportation.

Based on the enterprise's reliance on a large-scale municipal agricultural product platform in Jiangsu Province, its technological application advantages are not only limited to meeting the platform's basic import and export supply needs but also serve as an important supplementary link in designing urban cold chain logistics models. This study will focus on exploring the advanced layout of the provinces and cities where the enterprise is located and combine it with the urban radiation theory and demand data of cold chain logistics in existing research to analyze and summarize how to use the transformation results of technological innovation, combined with the construction of supporting infrastructure, to solve industry problems. Common "breaking chain" issues to provide transferable design ideas.

3 Case Analysis & Suggestions

As an important hub for China's resource balancing projects such as "transferring vegetables from the south to the north", "transferring vegetables from the north to the south", and "transferring fruits from the west to the east", Nanjing gathers agricultural and sideline products from China and even the world. In 2021, Nanjing achieved a trading volume of 13.87 million tons of agricultural products and a trading volume of 100 billion yuan, ranking first in Jiangsu Province and top three in the country in terms of trading scale, supplying the consumption needs of more than 35 million people in the Nanjing metropolitan area and its surrounding areas. The supply of agricultural products accounts for more than 80% of Nanjing and its surrounding areas.

Nanjing's cold chain logistics has developed rapidly, with more than 100 cold chain logistics companies above the designated size in the city and a total cold storage volume of 2.1 million cubic meters. As the only megacity in Jiangsu Province, Nanjing currently has a per capita cold storage capacity of 0.22 cubic meters per person, higher than the national average. However, there still needs to be a significant gap at the international level. Benchmarking against the level of developed countries, according to the standard calculation that the per capita cold storage capacity will reach 0.4 cubic meters per person in 2025 and 0.45 cubic meters per person in 2035, the cold storage demand in Nanjing will reach 4 million cubic meters in 2025 and 6 million cubic meters in 2035. The cold storage gap will reach 3.9 million cubic meters by then.

As shown in Figure 1, to cope with the cold storage logistics gap, Nanjing City, relying on the PCM technology of the technological innovation conversion results of enterprises, proposed to set up two cold chain base areas with evident functional complementarity in Jiangning District, the geometric center of the Nanjing Metropolitan Area, using the traffic layout network located on the Yangtze River Grand Channel.

Fig. 1. Cold chain logistics base location selection in Nanjing

Variety complementarity: The East District mainly comprises fresh agricultural products such as fruits and vegetables and aquatic products. In contrast, the West District primarily comprises frozen foods such as meat and seafood.

Functional complementarity: The East District is close to the main urban area and is mainly responsible for the distribution, cold chain distribution, and emergency supply of fresh agricultural products. The cold chain logistics facilities are mainly low-temperature trading, fresh-keeping refrigeration, and low-temperature processing. The West District is slightly farther from the main urban area. It undertakes low-temperature warehousing, regional distribution, centralized supervision of imported cold chain foods, and emergency supply of frozen foods. Cold chain logistics facilities mainly deal with frozen warehousing, processing, and distribution.

Both areas are adjacent to the highway entrance and exit and are only 20 kilometers apart. A dedicated freight line has been provided.

By reviewing the experience cases in Nanjing, we can find three common factors in the site selection of cold chain bases.

Relying on the core transportation network: The site selection of the base should prioritize transportation convenience and be close to important transportation hubs such as highways, railways, and ports to ensure the rapid and efficient transportation and circulation of agricultural products.、

Close to the central urban area: The base should be set up in the marginal area of the central urban area to serve the metropolitan area quickly and, at the same time, facilitate the input of rural agricultural products and realize the efficient circulation of agricultural products.

Efficient use of land resources: The site selection of the base should fully consider the utilization efficiency of land resources, reasonably plan the layout, avoid land waste, and improve land utilization.

The layout design of regional cold chain logistics bases needs to consider infrastructure scale (cold storage demand capacity) and location selection, as well as pay attention to the innovation of application technology. Traditional mechanical refrigeration technology, which uses Freon as the main refrigerant, is mature but has many disadvantages, making it difficult to cope with industry difficulties. Taking Nanjing as an example, the industry generally faces problems such as insufficient cold storage in the production area, difficulty

in using cold chain vehicles, high energy consumption in small cold storage, large safety hazards, long circulation chains, and high one-stop cold chain costs.

The PCM technology mastered by the company selected in the case provides new ideas for the layout design of regional cold chain logistics bases. Using PCM cold storage to store refrigerant energy quickly through valley electricity can significantly reduce energy consumption and electricity costs, more accurately control temperature fluctuations and moisture loss, and extend the shelf life of vegetables, fruits, and meat products. The shelf life is more than 30 days, significantly reducing losses. The PCM container project moves the convenient cold chain unit to the source of agricultural product production, complements the shortcomings of the cold chain supply chain, and achieves large-scale, professional, and intensive cold chain development. In actual operation, it saved 5% of the first kilometer and the entire 7% product loss in the process improves the efficiency and economic benefits of cold chain logistics. Therefore, the layout design of regional cold chain logistics bases needs to be combined with technological innovation. New cold chain technology represented by PCM technology can effectively solve the shortcomings of the traditional model and promote the upgrading and development of the cold chain logistics industry.

4 Discussion

Although technological innovation can effectively alleviate the difficulties of existing technologies, new technologies face challenges due to their late emergence, insufficient development, and initial market promotion.

The new PCM technology involved in the case required substantial investment during the early stages of research and development. As it is still in a self-sufficient adaptation stage and has yet to achieve scale effects, the cost of new container units and conversion remains high, making it difficult for related companies to support. Therefore, the government needs to play an organizational role, provide support, establish demonstration models, and promote market integration.

In addition to capital investment, the construction of supporting facilities can rely on more than just a single enterprise. According to the application characteristics of PCM technology, the slow-released cold and heat energy comes from traditional mechanical refrigeration equipment, which is relatively independent and separated from the unit in the initial design. This separation allows for providing energy storage and maintenance functions for PCM containers through socialized services in a one-to-many format. Architecturally, the drop-and-hook container is part of the transportation and circulation link in cold chain logistics, and its network layout can be designed with reference to new energy vehicle charging stations.

Based on the characteristics of 1-2 hours of refrigeration and 72 hours of slow release, it is feasible to deploy 50% of refrigeration equipment around warehouses. For instance, if a company uses 80 cold chain vehicles per day, each requiring an average of 1.5 refrigeration, totaling 60 hours, and assuming a daily working time of 15 hours, approximately 4 sets of refrigeration equipment would be needed. The remaining 50% should be dispersed along the main transportation routes.

Taking the logistics network in the Yangtze River Delta region as an example, the maximum distance between cities is at most 500 kilometers, or a 10-hour journey. It is not necessary to deploy refrigeration units along the entire highway as with electric vehicle charging stations. On a larger scale, such as across China's 19 urban agglomerations, where the maximum distance between agglomerations is 4,000 to 5,000 kilometers (within a 60-hour journey), it generally is within the 72-hour journey limit, so additional refrigeration equipment is not required However, to account for non-ideal conditions, it is advisable to set up a certain number of refrigeration units at key intersections of major traffic arteries as a supplement.

To further optimize the layout architecture, the design principles of automotive blockchain charging stations can be referenced, and the initial design can be refined based on simulations of actual operations and demand data [11].

From the city's perspective, Nanjing's cold chain logistics layout model demonstrates comprehensive rationality and technological advancement, making it valuable for further promotion and application. From a regional perspective, as the only super-large city in Jiangsu Province, Nanjing is part of the Yangtze River Delta urban agglomeration, one of the world's six major urban agglomerations. According to evaluations by authoritative institutions, among the 27 large cities in the Yangtze River Delta region, there is one mega city (Shanghai), two super-large cities (Hangzhou and Nanjing), and 20 Type I and Type II large cities, with a few cities not classified as large cities.

Nanjing's "one main and one auxiliary" cold chain storage base model can serve as a reference for other cities' planning and construction. For instance, Shanghai can adopt the "one main and two auxiliary" model as a higher-level megacity for its cold chain storage planning and development. Each city should plan cold chain logistics according to its level and infrastructure capabilities. In the Yangtze River Delta region, this approach can create a "1 × 3+2 × 2+24 × 1" cold chain storage system comprising 31 bases to meet the basic regional cold chain needs. This layout model also applies to other urban agglomerations of a specific scale.

5 Conclusion

This study examines the application of PCM technology in cold chain logistics in Nanjing, analyzing and summarizing an innovative layout model that combines traditional methods with new technologies. This model provides valuable insights and references for cities and international urban agglomerations in China and worldwide in their efforts to adopt advanced technologies.

However, the success of this model in promoting the further development of the cold chain logistics industry hinges on the continuous advancement of technology. PCM technology, central to the cases analyzed, requires ongoing innovation to sustain its market value. Research should expand from single-category applications to cross-disciplinary studies, transforming feature testing into scientific exploration. For instance, alongside the cold chain logistics network for agricultural products discussed in this study, in-depth research on the toxicity and side effects of the PCM core refrigerant and its compliance with national food safety standards is essential. Reliability challenges such as cold storage ratio, refrigeration time, stability, balance, and corrosiveness must also be addressed for the large-scale application of PCM.

Furthermore, drawing on the development history of new energy vehicles, a hybrid development model could be employed to formulate market promotion strategies for PCM technology. The transition from traditional technologies and models to new ones is a gradual process. The development of hybrid cold chain units that integrate both traditional and new technologies is crucial for the future application prospects of PCM technology.

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