Research on cooperative optimization of terminal distribution of Chongqing underground logistics system based on metro network

Wenjie Liao

Chang'an Dublin International College of Transportation, Chang 'an University, Xi 'an, Shaanxi, 710018, China
Email: wenjie.liao@ucdconnect.ie

Abstract:

This thesis presents a novel solution for the distribution problem in the urban underground logistics system, specifically addressing the challenge of the "last kilometer" distribution during the non-operating hours of the Chongqing metro system. The study commences by examining the present condition and significance of subterranean logistics systems. It thoroughly analyzes the distinctive topography and traffic obstacles specific to Chongqing's underground logistics system, and highlights the practicality and advantages of utilizing the metro system for logistics and distribution. The thesis proposes a comprehensive metro logistics and distribution system, which includes the selection of transfer locations, efficient connection between distribution centers and metro stations, and the implementation of appropriate management and scheduling strategies for distribution trucks. This study presents a unique approach by effectively combining the metro system with urban logistics requirements. It offers a fresh perspective on addressing the main challenges in urban logistics and distribution. Additionally, it provides a comprehensive theoretical and practical framework that can be applied to other regions with similar urban characteristics.

Keywords: Urban Underground Logistics, Metro Network Utilization, Chongqing City, Last Mile Delivery

1. Opening statement

The continuous growth of metropolitan areas has brought new challenges to traditional ground logistics and distribution methods. The traditional distribution model is overwhelmed by the increasing distribution demand, and the "last-mile" distribution challenge faced by e-commerce courier companies is particularly significant, serving as a major obstacle in this industry. Nevertheless, the expansive reach and substantial capacity of urban rail transit potentially make it a crucial solution for addressing logistics and distribution challenges. Hence, this research focuses on Chongqing, a city characterized by its mountainous terrain, and aims to explore efficient strategies for utilizing the metro network for nighttime logistics delivery during periods of metro suspension. This has the potential to not only offer a practical answer for us, but also to introduce a fresh perspective on the advancement of urban logistics and distribution models.

2. Review of existing literature

In 2013, Liu introduced the idea of underground logistics, highlighting its capacity to facilitate the movement of commodities using subsurface pipelines and automated transportation methods. Chen et al. (2023) suggested that subsurface logistics systems can effectively mitigate urban traffic congestion and enhance distribution efficiency. The UK's completely automated mail transit system, which was founded in 1927, served as a prototype for the development of underground logistics (Liu 2013). Germany and the Netherlands have achieved notable advancements in underground logistics technology, particularly in the development and execution of urban logistics networks. Japan has conducted a study to determine the practicality of implementing an underground logistics system in its densely populated urban areas. The study specifically examined the system's ability to operate efficiently and handle tasks in a standardized manner (Hu et al., 2023). These advancements indicate that subsurface logistics networks have the potential to not only alleviate surface traffic congestion but also enhance urban transportation efficiency. Nevertheless, Wang et al. (2023) highlight the fact that underground logistics systems encounter substantial expenses and technical obstacles. They propose that subterranean logistics should be coordinated in conjunction with above-ground systems, particularly for the final leg of distribution. Presently, the majority of study has concentrated on certain technologies or applications, however, there is a dearth of comprehensive research on the entire system. Further investigation should focus on developing a comprehensive subterranean logistics infrastructure, encompassing interconnected networks, storage facilities, and distribution channels, taking into account all relevant factors.

3. Analysis of the Current Situation of Chongqing Metro Network and Logistics System

3.1 Chongqing Metro Network

Chongqing currently possesses 11 metro lines, which span over 500 kilometers in total length. These lines serve as connections between significant commercial and residential zones, as well as popular tourist destinations. Line 1 is oriented in the east-west direction and serves as a transportation link between significant metropolitan centers like Yuzhong and Shapingba to satisfy the primary transportation needs. On the other hand, Line 3 is a monorail line that travels in the north-south direction and extends to the airport bonded area. Its purpose is to alleviate passenger congestion and stimulate economic growth.

The site analysis reveals that the subway station in the city center is characterized by high population density, while the density steadily decreases as one moves towards the suburbs. The daily traffic at Xiao Shizi station is 150,000, which indicates its role in distributing passengers. In contrast, suburban stations like Luqi station have a more consistent passenger flow and a spacious traffic environment.

Regarding capacity, during peak periods, such as Line 6, the frequency of classes is approximately every 3 minutes, while during off-peak periods, it is adjusted to every 5 minutes. This adjustment aims to strike a balance between efficiency and cost-effectiveness. During some holidays, Line 3 is capable of accommodating up to 650,000 passengers in a single day, demonstrating its significant capacity for transportation.

3.2 Chongqing Logistics System

3.2.1 Chongqing Logistics Center

The logistics parks in Chongqing's main urban regions exhibit two primary features: positioning on the outskirts of the city center and positioning along major transportation routes. The presence of mountainous topography and economic considerations have resulted in the clustering of logistics parks on the outskirts of urban centers. The high cost of land in core areas and the inclination towards lower land prices have played a significant role in driving this pattern. The government's goal of "retreating from two to three" and land use planning have a tendency to relocate logistical and industrial regions towards the outside of the city.

Logistics parks primarily depend on crucial transportation facilities, such as Cuntan Port and Orchard Port, and exploit the Yangtze River Three Gorges waterway, train freight, and highway network to establish the benefit of multimodal transportation via water, land, and air. Due to the strong need for efficient and cost-effective transportation in contemporary logistics, logistics parks are strategically situated near transportation hubs to guarantee smooth integration of various transportation modes.

The Cuntan Port spans around 2,675 acres and is furnished with seven container berths capable of accommodating 5,000-ton vessels, as well as two automobile ro-ro terminals. It has an annual capacity to handle 1.4 million TEU containers and 300,000 vehicle ro-ro units. The geographical position and multi-modal transportation network of this location create a unified logistics hub that offers direct access to European rail freight, Chongqing Jiangbei Airport, and major cities throughout the country. This strengthens its strategic logistics position in Chongqing and the entire southwest region.

3.2.2 Logistics requirements

Due to the growth of e-commerce platforms, the express delivery industry in Chongqing handled a total of 979 million shipments in 2021, marking a 33.97% increase compared to the previous year. The income generated by the express delivery business amounted to 10.343 billion yuan, reflecting a 24.58% increase year-on-year. An extensive range of everyday commodities, including apparel, household appliances, and food, are consistently transported to individual residences via the logistics network. The majority of these products originate from industrial clusters located along the eastern seaboard, forming a bustling east-west logistics corridor.

3.2.3 Logistics challenges

The primary obstacles confronting logistics in Chongqing encompass traffic congestion and logistical delays arising from the intricate topography, alongside the market's equilibrium of supply and demand occasionally leading to shortages. The mountainous terrain and rivers in Chongqing pose a challenge for express delivery routes, resulting in indirect or congested paths. During peak commuting hours in 2022, the average speed of express delivery is 29.84 kilometers per hour, and there is an average delay of 40.06 seconds at signalized intersections. Furthermore, logistics and transportation make a substantial contribution to urban pollution. China's Ministry of Environmental Protection (MEP) predicts that transportation emissions would contribute to 10.4% of the country's carbon emissions by 2022. Among transportation emissions, road transportation will be responsible for over 85%, making it a crucial sector for reducing emissions.

4. Discussion of Strategies for the Operation of Subway-Based Underground Logistics Systems

4.1 Significance of synergistic operation

4.1.1 Economic value

The cooperative operation strategy optimizes logistics and transportation costs and improves transportation efficiency at the economic level, while promoting the sustainable development of urban logistics system.

Improvement of time efficiency: The stable operation mechanism of the subway network and the scheduled routes significantly improve the anti-interference ability, effectively avoiding road traffic congestion and emergencies, and ensuring the timeliness of goods delivery.

The level of resource optimization: the coordinated operation of the metro network reasonably optimizes the ground cargo resources. Underground logistics system has advantages in space utilization, high capacity, automation, transportation safety and cost.

Wide logistics space: the underground logistics system makes logistics resources flow and reorganize in a wider geographical scope due to the automation and large-scale transportation. It promotes the smooth conduct of transportation, loading and unloading, storage, circulation processing and information management, forming an efficient production and distribution chain.

4.1.2 Social significance

The subway-based subterranean logistics system efficiently alleviates the burden on surface transportation and mitigates the likelihood of traffic collisions. Based on 2016 data, almost 90% of vehicles in China are utilized for the purpose of transporting goods, and the introduction of an underground logistics system may efficiently alleviate the burden on urban logistics and separate logistics transportation from urban mobility. This not only diminishes the number of urban transportation vehicles and alleviates traffic congestion, but also mitigates the likelihood of traffic accidents caused by huge trucks and enhances safety. The underground transportation system accomplishes the dual objectives of decreasing the quantity of ground-based freight vehicles and enhancing traffic safety.

4.1.3 Ecological significance

An underground logistics system based on subways can significantly decrease urban car emissions. Conventional urban freight transportation primarily depends on heavy-duty vehicles, which generate harmful pollutants like carbon oxides, sulfur oxides, and phosphorus oxides due to inefficient fuel combustion. Participation of metro systems in logistics can decrease the use of freight vehicles on roads and lower exhaust emissions. Simultaneously, enhancing the stability and consistency of the system enhances energy usage efficiency and further advances environmental preservation.

4.2 Forms of cooperation

4.2.1 Formation of passenger and freight mixture

The planned subway underground logistics system primarily involves the integration of passenger and cargo transportation by the addition of freight carriages to typical subway trains, allowing for shared lines and efficient logistics distribution. The benefit of this method is in minimizing the need for extensive modifications to current rail transportation infrastructure and maximizing the utilization of pre-existing underground areas. Nevertheless, it depends on a sophisticated automated operations scheduling system to guarantee smooth transit of passengers and goods. To maintain the overall rail transit service level, it is imperative to prevent any delays or faults throughout the loading and unloading operation.

4.2.2 Form for Specialized Freight Trains

Special freight trains are a type of coordinated operation focused on transporting goods by substituting or supplementing passenger trains with freight trains on the subway network. The freight train mitigates the interdependence between passenger and freight transit and enhances safety, in contrast to a mixed passenger and freight system. To implement this approach, it is necessary to modify the current metro stations and lines. This includes adding separate freight lines and platforms, while ensuring that passenger and freight platforms are properly separated to prevent any interaction. A dedicated freight train offers the benefit of segregating passenger and freight tracks, hence enhancing safety. Nevertheless, this mode necessitates a substantial investment in modifications, incurs significant expenses, and reduces the initial passenger capacity, rendering it inappropriate for segments with strong passenger demand.

4.3 Problems and challenges

4.3.1 Challenges of technology and equipment

The key to the synergistic operation of metro and underground logistics systems lies in the functionality and efficiency of loading, storage, and transportation equipment. Challenges include:

(1) Lack of loading and unloading facilities: Existing metro stations are not equipped with specialized cargo loading and unloading facilities, such as elevated platforms or automated systems. Building these facilities would require significant investment and could impact passenger mobility and safety. 2.

(2) Insufficient storage space: Effective logistics management requires adequate storage space, but finding such space in metro stations, especially in busy areas, is a challenge.

(3) Transportation equipment limitations: Traditional metro train designs focus on passenger safety rather than cargo transportation. Investment in specially designed trains is required, involving capital and O&M costs.

(4) Technology interfacing and upgrading: Implementation of an underground logistics system may require new technologies, such as logistics tracking and automated management systems, which require compatibility with existing subway technologies, involving technology integration and upgrading.

(5) Safety standards and regulations: The introduction of logistics operations will require adherence to strict safety standards, including screening for hazardous materials and ensuring operational safety.

4.3.2 Complexity of operations management

Scheduling and time management

The introduction of freight in a high-density metro network requires precise scheduling. Freight and passenger traffic on shared tracks need to coordinate their schedules to avoid mutual interference and respond to emergencies through a dynamic scheduling system that quickly adjusts resources and time.

Emergency Response Mechanisms

Integrating freight transportation requires a well-developed emergency response mechanism. When system delays or failures affect cargo and passengers, consideration needs to be given to the nature of the cargo, storage, alternative transportation options, and passenger safety, in order to minimize impacts and properly address the problem.

4.3.3 Infrastructure Adaptation and Investment Efficiency

Adaptation and optimization of metro system infrastructure: In order to adapt to freight transportation, existing metro platforms, tracks, signal systems, etc. need to be adapted and optimized, which requires a large amount of capital and scientific planning.

Investment Benefit Analysis: The high initial investment and long payback period of the project need to be evaluated through rigorous cost-benefit analysis to ensure the economic benefits are reasonably predictable, in order to gain support from investors and decision makers.

5. Design and Analysis of End Distribution Collaboration Program

5.1 Location Selection Principles

5.1.1 Selection of an external site

(1) Evaluation of the proximity between the garage and the subway station

The proximity of distribution facilities and transportation hubs has a substantial impact on logistics efficiency. Using Chongqing as an illustration, a sensible approach for selecting a distribution center is to go for a garage situated within an approximate radius of 1 kilometer from a Line 1 metro station. This recommendation is based on the data indicating an average distance of 1.9 kilometers between subway stations.

(2) Radiation capacity of subway stations

Subway stations of considerable size and stations located in residential areas with a significant need are of particular significance for logistics operations. Large stations are advantageous for managing substantial logistics demand since they offer ample space and facilities. On the other hand, residential area sites are beneficial due to their large order volumes and a consistent customer base. Hence, when choosing locations, it is possible to loosen distance limitations for certain places in order to achieve extensive distribution coverage and optimize timeliness. This is done with the objective of enhancing distribution efficiency and catering to a larger array of requirements.

5.1.2 Intranet Location Determination

(1) Factors to Consider Regarding Geographic Location

The site selection process should prioritize a site with ample space to accommodate storage, operational, and logistical equipment requirements, without causing disruptions to the regular traffic flow of the garage. To minimize conflicts in logistics operations, it is advisable to steer clear of main entrances and exits as well as high-traffic areas. Additionally, positioning the activities adjacent to the channel exit facilitates swift entry and exit of goods.

(2) Considerations about safety and the environment

Optimal site selection should prioritize proximity to fire escape routes to ensure adequate ventilation and minimize exposure to probable hazard zones. Simultaneously, it is crucial to take into account environmental aspects such as illumination, temperature, and humidity in order to uphold the quality of goods and ensure the safety and comfort of the personnel, hence enhancing job productivity.

5.2 Distribution process

In order to improve the efficiency of end-to-end distribution, this study designs the distribution process from subway station to client, which is divided into two parts:

Nighttime subway station to garage distribution: at night, the time window after the end of subway operation is utilized to transfer goods through a dedicated receiving area and a transmission corridor designed for unmanned delivery vehicles. Goods are sorted upon arrival at the garage in preparation for the next day's delivery.

Daytime Garage to Client Delivery: Based on the handling and sorting done during the night, the unmanned delivery vehicles begin their on-time delivery tasks during the day, ensuring an efficient and consistent process.

5.3 Operation and Management

5.3.1 Determining the length of the time window and the starting and ending points

(1) Maintenance in off-peak and interval operation

The metro's daily operational data indicates that the morning peak hours occur from 7:00 to 9:00, while the evening peak hours occur from 17:00 to 19:00. The remaining hours of the day are considered non-peak hours. Scheduling of emergency or small-scale maintenance work, such as track inspections and vehicle repairs, is possible during peak hours. It is crucial to tightly regulate the time frame and extent of these tasks in order to avoid disrupting regular operations. This will necessitate prompt action from the maintenance team and efficient communication with the operation team.

(2) Sectional maintenance of lines and freight services

To achieve a balance between the distribution of commodities and the upkeep of routes, the routes are separated into segments, such as A, B, and C. As an illustration, during a route, segment A is responsible for distribution in the first week, while segments B and C are maintained. In the subsequent week, segment B takes over distribution, while the other segments are maintained. This rotational scheme guarantees that every line segment is involved in shipments and receives repair. Effective communication and coordination between the distribution and maintenance line segments are necessary to avoid operating disruptions and ensure a seamless interaction between the freight and maintenance schedules.

5.3.2 Clear definition of the right to use the line

Using Chongqing's metro network as an illustration, if repair work is scheduled for Line 3 on a specific night, the delivery strategy should proactively avoid this line and reroute delivery operations to alternative lines like Line 1 and Line 6. The execution of this approach relies on the examination of the Chongqing metro's operational data and necessitates meticulous coordination among the distribution, operations, and maintenance teams to guarantee clarity and effectiveness in route utilization.

5.3.3 Nighttime Dispatch Strategy

An optimization of the nighttime delivery scheduling technique is required to suit the unique lines and station layouts of the Chongqing Metro. One strategy to enhance the efficiency of vehicle usage is to centralize orders for the same or comparable lines, such as Line 2 and Line 3. Simultaneously, the cargo's attributes such as volume, weight, and fragility are considered. For instance, valuable or delicate cargo being transported from Niu Jiao Tuo to Liang Jie Kou station may require separate delivery or special handling. Furthermore, the distribution strategy should encompass the careful selection of stations, accurate traffic prediction, and effective emergency response mechanisms to guarantee precise distribution and effectively handle unexpected situations.

6. Analysis of risks and challenges

6.1 Risk identification

The subway logistics terminal distribution coordination in Chongqing faces various risks. These include technological risks, which involve uncertainties regarding the effectiveness of system implementation and its compatibility with the metro network, as well as rapid technological updates. Economic risks are also present, which are associated with construction costs, taxes, and changes in financing. Operational risks encompass factors such as raw material costs, energy expenses, industrial connections, metro operation time, and passenger flow. Organizational and management risks involve the automation of logistics systems and coordination with metro management. Lastly, environmental risks include socio-political factors, changes in the financial market, policy and regulatory changes, and the impact of urban metro construction on the natural environment. These risks can significantly affect underground logistics systems.

6.2 Risk response

In the face of the multiple risks associated with a metro-based urban subway logistics terminal distribution system, a comprehensive response strategy is required:

Technical risk: Implement in-depth technical assessment and pilot projects to ensure that the technology is compatible with the subway system, and keep an eye on technical updates.

Economic Risks: Set up a risk fund with strict budget

control and seek funding from government or partners.
Operational Risks: Diversify raw material and energy supply, and establish linkage with metro operations.
Organizational Risk: Conduct regular staff training, optimize management mechanism, and establish a communication and coordination group with metro management.
Environmental Risks: Continuous monitoring of political, economic and regulatory changes, development of contingency plans, and environmental impact assessment to ensure sustainable development of the project.

7. Feasibility analysis

7.1Technical feasibility

The crucial aspect of integrating Chongqing's metro network with the Underground Logistics System (ULS) lies in the comprehensive utilization of urban infrastructure, encompassing the metro network as well as other amenities like tube corridors and underground roads, to optimize resource conservation and enhance infrastructure efficiency.
The efficacy of subterranean logistics systems hinges on the implementation of automation and information technology, encompassing automated transportation vehicles, intelligent tracking systems, and logistics information management, with a strong emphasis on safety and dependability. Ensuring the system's stability relies heavily on the maintenance and safety management. Technological advancements encompass autonomous driving, intelligent warehousing, and optimized energy use, with the goal of enhancing efficiency and promoting sustainability. The challenges encompass the strategic planning of underground logistical routes, managing the interfaces with surface traffic, and assuring the stable operation of the system in intricate surroundings.

7.2Economic viability

Cost reduction: The synergistic operation of the Metro and ULS reduces construction costs by utilizing existing urban infrastructure and reduces operating costs by decreasing transit time and energy consumption.
Transportation Efficiency Improvement: Integration of the Metro and ULS allows for 24-hour transportation, speeding up the flow of goods with greater speed and accuracy, which has a positive impact on economic activity.
Indirect benefits: The synergistic operation reduces traffic congestion, improves environmental quality, enhances the quality of life of residents, attracts investment, and enhances the city's competitiveness.
Return on investment: Despite high initial costs, efficient long-term operation and low maintenance costs are expected to realize substantial economic returns. Sensitivity analyses are conducted to ensure that the project is economically viable under a variety of scenarios, taking into account the risks of technological innovation and market changes.

7.3 Social feasibility analysis

Public Acceptance: Increase public awareness of the system and introduce its workings and positive impacts through education and outreach. Enhance engagement with community residents, business partners, and government to respond to concerns through surveys and discussions. Maintain transparency of project progress and publicize environmental and safety audit results to build trust.
Social Benefits: Underground logistics systems contribute to environmental protection and sustainable development by reducing pressure on surface transportation. Ensure that the system complies with safety norms and establishes an effective emergency response mechanism to safeguard public and employee safety.

8. Conclusions and recommendations

8.1 Key Findings

This study comprehensively examines the underground logistics system and its complete distribution process in Chongqing. It suggests a novel approach: making use of the subway's non-operational hours for nighttime logistics and distribution, to address the challenge of distributing goods over the final kilometer. The study demonstrates that this approach can significantly enhance the efficiency and promptness of distribution, while also mitigating urban transportation congestion and environmental pollution. The paper develops a synergistic optimization model to offer both theoretical and practical direction for implementing the underground logistics system.

8.2 Theoretical and practical significance

This study enhances the existing body of knowledge on underground logistics by introducing new theoretical viewpoints and methodologies for utilizing metro networks. Practically, it offers specific methods for implementing underground logistics systems in Chongqing and other cities. Additionally, it demonstrates notable social and economic advantages by reducing urban traffic congestion and enhancing logistics efficiency.

8.3 Limitations and Future Directions

While the findings of this study have importance, they are constrained to the particular context of Chongqing and may not be generalizable to other urban areas.

Subsequent investigations should employ and authenticate these models and procedures in various urban categories to assess their applicability and efficacy. Furthermore, it is necessary to conduct additional practical tests and enhancements on the proposed synergistic optimization models. Potential areas for future research could involve investigating novel technologies and tactics, such as artificial intelligence and automation, to further optimize the effectiveness and security of subterranean logistics and distribution.

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