

## Research Article

# Urban Logistics Services Supply Chain Process Modelling Based on the Underground Logistics System via the Hierarchical Colored Petri Net

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The implementation of the urban underground logistics system (ULS) can effectively mitigate the contradiction between the surging logistics demand and the increased negativity of urban logistics. The widespread implementation of ULS still suffers from a lack of research into its operation in the marketplace, although the research on ULS system technology and network design appears to be sufficient. A new supply chain for logistics service based on ULS (ULS-SSC) was proposed, as ULS embedded in the urban logistics system could lead to the evolution of the role of supply chain participants. This article analyzed the organizational structure and operation characteristics of ULS-SSC and designed a top-down ULS-SSC operation process model based on the designed functional structure and subsystems relationship using the hierarchical colored Petri net (HCPN). The simulation results show that the integrated information management platform based on ULS can integrate urban logistics service supply chain resources and operate effectively under the two main service modes designed. The high-time delay intermediate links can be upgraded by system optimization, and the links with initial pickup and terminal distribution can be improved through outsourcing and supply chain collaboration. The findings provide new insights into the feasibility of the operation of ULS in the market and help stimulate the implementation of ULS.

## 1. Introduction

The unprecedented e-commerce boom has dramatically increased shipping practices in cities all over the world. Consequently, more logistics companies are competing in the urban freight market, and more vans, delivery stations, and couriers are being installed in cities. Increasingly poor urban traffic has also led to increasingly expensive and inefficient urban logistics. To alleviate this growing conflict, the interest in the concept of “moving freight from above to underground,” first proposed by Zandi and Gimm [1], has attracted the attention of researchers and professionals for more than 30 years. The underground logistics system (ULS), defined as a transport system for moving goods

between out-of-town logistics parks and in-town customers through underground tunnels or pipelines, is recognized as a clean, efficient, and smart mode of urban freight transportation to cope with the new demands of urban logistics [2]. Especially, ULS contributes to achieving peak carbon dioxide emissions in the transportation industry [3]. In addition, ULS' unmanned and intelligent transportation also supports COVID-19's requirements for contactless logistics and can enhance emergency response capabilities in urban settings.

As an infrastructure capable of handling the majority of urban freight needs, ULS is capable of all of the actions involved in managing, processing, and disposal of the freight, such as intracity trunk transportation catering for

different packaging types, transshipment with unpacking and crating processes, circulation processing, and warehousing and distribution processes [4]. Notably, hazardous and heterogeneous items are not included in the ULS transportation services, given locomotive loading constraints and system safety.

In the course of ULS development, several drivers in many industries, namely, legislation, economic interests, and social responsibility in the fields of transport, logistics, underground space, and urban resilience, have gradually led governments and companies to lay out an integrated ground-underground transportation network to respond to the new demands of urban logistics [5]. As an important logistics infrastructure for the realization of smart logistics and common distribution, the huge benefits have not led to the rapid mass adoption of ULS, with projects such as the Cargo-Cap underground freight transportation system in Germany [6] and the OLS-ASH project in the Netherlands [7] failing or stalling due to major obstacles of insufficient demand and huge investments. Until these two years, pilot projects began to be implemented in Switzerland (Cargo Sous Terrain) [8] and China (ULS in Xiongan New Area) [9].

However, ULS is more than just putting goods underground for transport. With a networked underground infrastructure, ULS incorporates the scattered logistics resources of the city, creating a new pattern of urban logistics by integrating the management of urban logistics in terms of cargo flow and process chain. The change in the perception of ULS from initially being just a new transport technology to now being seen as the core mode of urban logistics of the future reflects, on the one hand, the increasing social acceptance of ULS and, on the other hand, raises new questions about market operations in addition to intelligent transport technology systems and project investments.

The implementation of ULS might form a new urban logistics service supply chain (SSC) system structure, named ULS-SSC, under which the original supply chain participants have had a huge role change. Logistics resources and the original urban logistics providers would be integrated into the ULS-based urban logistics intelligent management platform to build a new logistics system [10]. The peculiarity of underground engineering makes the government as an indispensable subject to participate in the exploitation of the urban logistics market [3]. Given these new changes in supply chain elements, it remains unclear how the formation of ULS networks and commercial cooperation mechanisms interactively stimulate the development of ULS-SSC.

With the aforementioned in mind, this paper aims to describe the structure of ULS-SSC and design the operation process, under the new logistics service mode provided by ULS and the change of the supply chain participants' role. The hierarchical colored Petri net (HCPN) was adopted to design the process for the new SSC. In contrast to the traditional supply chain, the design of ULS-SSC took into account ULS-based substitution for surface trunk logistics transportation and multimodal synergy for last-mile distribution. The operational processes for two types of typical urban logistics goods, bulk goods and parcels, were designed to verify the effectiveness of the ULS-SSC model. By

analyzing the synergy between ULS and other supply chain subjects, combined with knowledge about the logistics service supply chain and the characteristics of the ULS system, this study proposed a set of ULS operational management analysis methods based on the ULS-SSC process, providing theoretical support for the practice of ULS in terms of operational feasibility.

The remains are organized as follows: Section 2 provides an overview of the related works. Section 3 explains the system features and the organizational mode. The functional structure of ULS-SSC is described, the hierarchical colored Petri net (HCPN) model is constructed to explain the operation of ULS-SSC in Section 4, and the validity of the model is verified by a case in Section 5.

## 2. Literature Review

### 2.1. A Brief Review of Previous ULS Studies

*2.1.1. System Technology and Application.* ULS, with the name of "Freight pipeline technology," was initially initiated to alleviate the negativity of freight traffic in cities. However, it is now even more widely recognized for its advantages in logistics and environmental protection [2]. Up to now, many underground transportation technology systems based on different traction powers have been successfully developed and put into application, such as pneumatic capsule pipeline (PCP) [11], Cargo-Cap powered by electricity [6], and Pipe\$net driven by Maglev [12]. A special blockbuster underground logistics line, Cargo Sous Terrain (CST) from Switzerland, with a length of 450 kilometers from Geneva to St. Gallen, has completed a feasibility study and started project financing for the first phase of the 65 kilometers project connecting Niederbipp/Härkingen and the city of Zürich (time horizon 2030) [8]. More pilot projects have been announced on the official platform, for instance, the ULS in Xiongan New Area [9], China. In the era of the grand development of underground space, the ceiling of underground engineering construction technology has been broken. ULS has become a silver bullet to alleviate the contradiction between increasing urban logistics and sustainable development due to its flexibility of layout and diversity of forms.

*2.1.2. Feasibility and Cost-Effectiveness.* Core equipment technologies for ULS, such as traction technology, locomotive traction technologies based on multiple types of power [13], and intelligent logistics equipment [14], are already proven technologies. Particularly, unmanned technology based on infrared scanning and 5G-based vehicle-object tracking positioning technology is already capable of meeting the technical feasibility of ULS implementation underground. High construction costs have been one of the most significant obstacles to the success of previous ULS projects, such as OLS-ASH in the Netherlands [7]. However, the growing negativity of urban freight, the urgent need for contactless transportation by COVID-19 [15], and low-carbon sustainable initiatives [16] provide new drivers for the development of ULS. The comprehensive benefits of ULS

applications are reflected in all aspects of future smart city needs, including traffic [17, 18], logistics [2, 19], environment [3, 10], and society [5, 20]. Although the construction investment is large, the cost benefit under the scale effect realized after the network operation would be gladly accepted by local governments.

*2.1.3. Two Main Research Streams Distinguished by the System Form.* One stream is the construction of a new independent ULS network in the urban underground. Binsbergen and Bovy [20] first proposed a mechanism for the operation of ULS networks. Considering multiobjective optimization such as cost, efficiency, and resource allocation, a hierarchical hub-and-spoke network containing multiple pipe diameters may be the optimal network form for ULS [21]. Another stream is that Metro-based ULS utilizes the metro network to realize the coordinated transportation of passenger and freight trains [22]. This model is subdivided into passenger-cargo separated type [23] and trailer-type [24]. The advantage of Metro-based ULS is to fully utilize and exploit the surplus potential of the urban metro network, thus saving investment. In contrast, it increases the difficulty of joint scheduling and network reliability management [25].

*2.1.4. The Gaps in Operations Management.* Past research by technologists has simply assumed that ULS is an underground transportation technology that moves freight underground, focusing on aspects such as the system technology [6, 8], network design [22, 24], and the macrobenefits of ULS [3, 5]. The revolutionary impact of this innovative technology on the entire urban logistics supply chain and the synergistic organizational relationships of the participants in ULS operation are overlooked, issues that will be decisive for the implementation of ULS. The ULS network is planned with the overall urban logistics industry in mind. It is inevitably operated by an independent and government-backed operator [5]. The intelligent and efficient underground transportation network in an unmanned environment greatly improves the efficiency and organization of urban logistics and thus generates new supply chain cooperation models [18]. Therefore, in the new urban logistics model under unified management, the role of government and traditional logistics enterprises in the supply chain process has changed and a new competition and cooperation relationship will be formed.

*2.2. Urban Logistics Service Supply Chain.* The complexity of intracity transportation makes urban logistics a unique segment in the logistics industry that has been spun off from the product supply chain [26]. The quality promotion of logistics services has contributed to the formation of the urban logistics SSC, which includes business processes such as transportation, warehousing, circulation processing, and delivery [27]. The usual structure of urban logistics SSC is shown in Figure 1, which takes logistics service integrator as

the core and relies on an information management platform to integrate functional logistics enterprises and other related service providers [28]. The logistics service integrator coordinates the operation of functional logistics service providers according to the logistics demand accepted and released by the integrated information management platform.

The fast-changing business model of urban logistics and the rapid growth of demand have supported urban development and people's lives while also bringing a lot of negative effects. In China, the annual growth rate of the express delivery business alone has exceeded 20% since 2015 and the annual growth rate of intracity service has exceeded 30% [29]. The huge volume of freight transportation has aggravated urban congestion, environmental pollution, and land resource shortage.

The development of urban logistics SSC oriented to improve the negativity of urban logistics has yielded little success. Many innovative initiatives, such as multimodal transportation [30], green supply chains [31], and investments in green technologies [32], have been instrumental in reducing the environmental impact of freight transportation. However, these initiatives have been virtually ineffective in reducing traffic congestion and reducing land use [18]. In recent years, the use of electric vehicles for deliveries began to be advocated [33], but instead of substantially alleviating congestion, many supporting charging facilities needed to be built, increasing logistics land use [34]. Widely discussed smart concepts such as drone delivery and unmanned vehicles are not applicable for large-scale urban use [35].

In short, logistics intelligence relying on ground transportation has always failed to achieve global goal optimization:

- (i) Restrictive policies exacerbate the conflict between limited urban road resources and the growth of logistics demand, which makes it difficult to carry out effective optimization of urban logistics SSC.
- (ii) In the market-led urban logistics system based on road transportation, the main body of the logistics SSC is unable to carry out technological innovation from urban logistics as a whole. This requires local governments to innovate urban planning concepts and upgrade logistics infrastructure to cope with the transformation needs of urban logistics.
- (iii) The urban logistics system is filled with a large number of homogeneous enterprises, resulting in a lack of cooperation and resource sharing in the logistics service supply chain [36].
- (iv) The formation of multiple SSCs in the urban logistics industry cannot be managed in a unified manner. Such SSCs that simply cater to a single type of demand is more concerned with cost reduction than intelligence, green and efficiency improvement [37].

Therefore, based on the networked underground logistics infrastructure, ULS-SSC integrates the management of

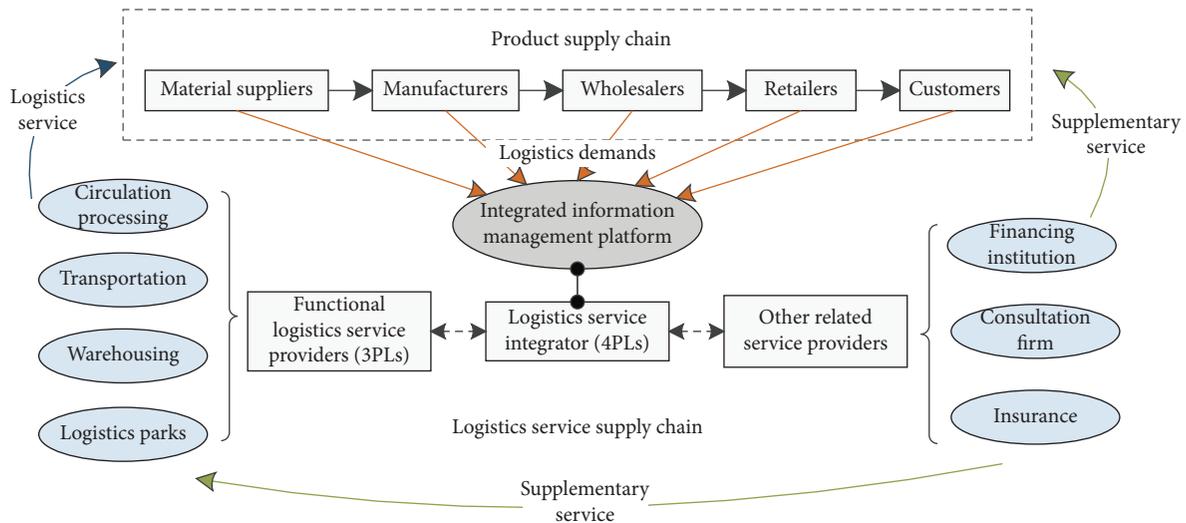


FIGURE 1: The structure of logistics SSC.

multitype logistics SSCs and enables the sharing of urban logistics resources, which can break through the bottleneck of the sustainable development of traditional road logistics SSC.

**2.3. Petri Net Method.** Petri net method is a mathematical expression of a discrete parallel system proposed by Carl Petri in 1962 [38], consisting of elements such as place, transition, directed arc, and token. Petri net has significant advantages in describing and analyzing the information and control flow in discrete event dynamical systems with asynchronous or parallel nature [39] and can provide formal and efficient support to model build and analysis [40]. Many advanced Petri net approaches have been developed to improve the limitations of the original model. For example, the hierarchical Petri net is suitable for industrial production systems, simplifying complicated systems into hierarchical subnetwork structures, thus controlling the functional units [41]. Modular Petri net can effectively resolve the issues such as state space explosion due to the advantages of easy scalability and better maintainability [42].

Petri net is well able to simulate large-scale discrete events, such as logistics and supply chain systems, and to find solutions quickly [43], especially Petri net with integrated hybrid modeling techniques performs better [44]. In this article, the HCPN was adopted to build and simulate the ULS-SSC system. HCPN integrates the colored Petri net proposed by Kurt Jensen [45] and the hierarchical Petri net, which can improve the shortcomings of traditional Petri nets that lack hierarchy and feature description.

### 3. Descriptive Analysis of ULS-SSC

Based on the basic composition of the supply chain system [46] and its evolution in ULS application scenarios, a proposed methodology framework for the structural design

and rationality verification of ULS-SSC consists of (1) a description of the composition of the ULS physical layered network, (2) the structure of ULS-SSC, (3) an analysis of the relationship between ULS and 3PLs in ULS-SSC, and (4) a deconstruction of service mode.

**3.1. Description of the Physical Layered Network.** From the perspective of solving the diversity of urban logistics and overall planning and design, a layered ULS network and ground transportation system together constitutes a multimodal distribution physical network. This network is the physical carrier of ULS-SSC, and its characteristics determine the structure and operation mechanism of the ULS-SSC.

Figure 2 illustrates the urban multimodal distribution physical network jointly constituted by a two-layer ULS network and ground transportation system. A two-layer ULS network comprising the primary network (tunnel diameter 8–10 meters) and the secondary network (tunnel diameter 4 meters) has been proposed and repeatedly verified to meet the logistics needs of a megacity, such as Beijing [47, 48].

The operation mechanism of the network covers the entire process of goods from the logistics park to the customer. The goods on the primary network will be distributed to the branch network (m1 to m2) or sent to the ground by vertical transport (m1 to m3), depending on the flow direction. Then, the network and ground transportation together constitute a synergistic logistics mode. We run the previous process in reverse and add a goods collection link at each node to achieve reverse logistics [47].

Terminal transportation, defined as the transportation process between the last node and the customer, takes various forms. For example, small conveyor belts can be built or drones can be used to deliver goods to smart parcel lockers, or they can be delivered manually. Parcel collection and delivery services based on shared systems can also be designed. The diversity of terminal transportation forms will also give rise to a variety of service outsourcing models.

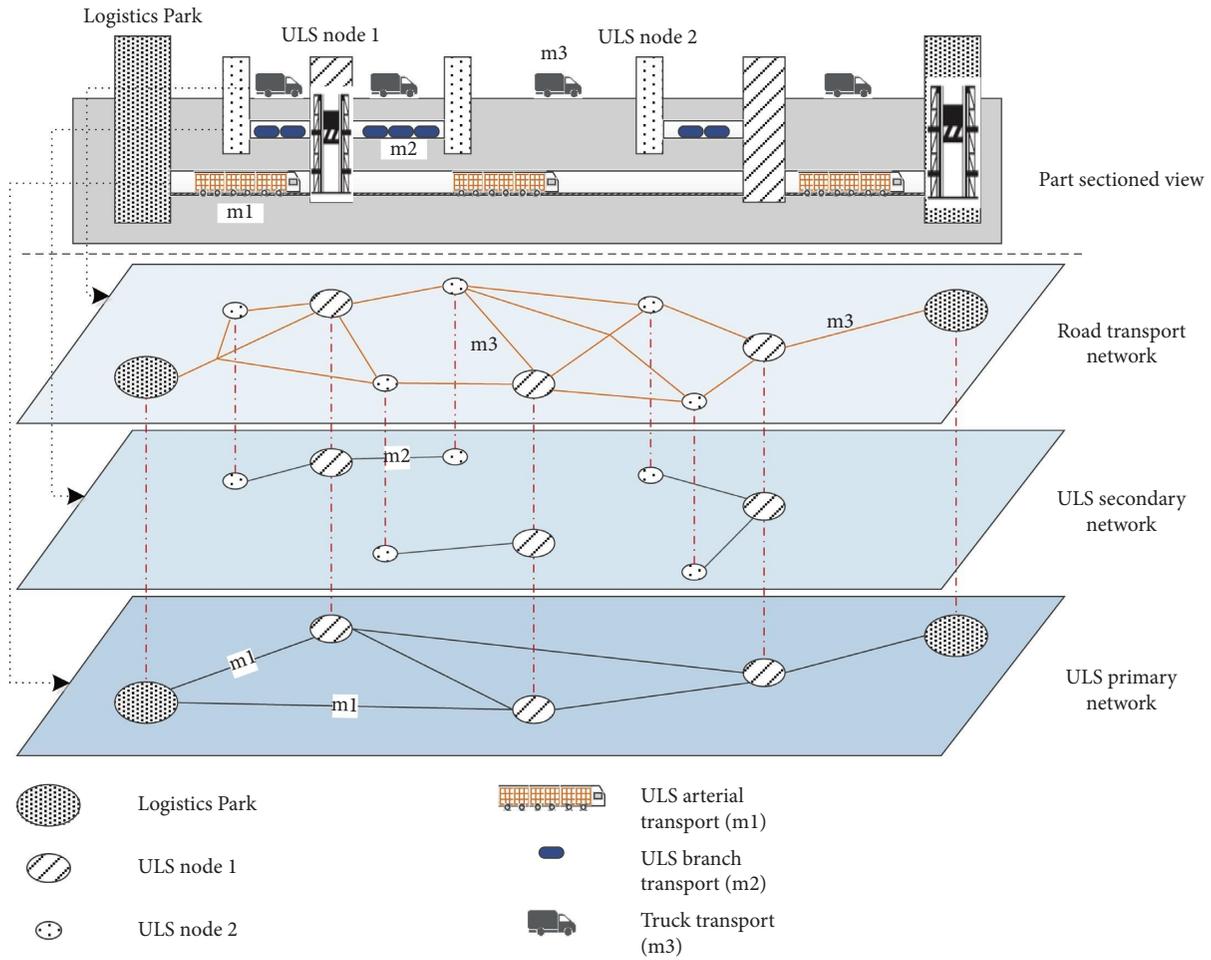


FIGURE 2: The physical network structure of ULS.

3.2. *The Structure of ULS-SSC.* ULS replaces ground truck transportation and can innovatively promote the development of the urban logistics SSC management to low carbon, efficient standardization, and a high degree of unmanned. It relies on the underground network infrastructure to connect the upstream and downstream and integrate the multifunctional services of the logistics SSC. Thus, with the development of a physical network, a ULS-SSC with a large capacity and multiple service types will be gradually formed.

Figure 3 shows the system structure of ULS-SSC. ULS-SSC intelligently integrates above-ground and underground transportation network, storage, circulation processing, and other resources to optimize the allocation of urban distribution resources, so as to provide personalized logistics services to customers with different requirements. ULS, the third-party logistics (3PLs) enterprises, and consumers are the three main participants in the ULS-SSC:

- (i) ULS can be divided into the integrated information management platform and the infrastructure platform. The former platform performs functional logistics resource integration and order management and transmits system operation requirements to the infrastructure platform. The infrastructure platform carries out the operation of the physical

system and completes the consumer-oriented logistics services. Moreover, the integrated information management platform coordinates the supply of other supplementary services related to the supply chain such as logistics finance, consulting and planning, business, and taxation.

- (ii) The third-party logistics (3PLs) enterprises, currently the main provider of logistics services, are still fully responsible to the customers in ULS-SSC but also can outsource intracity distribution operations to ULS. Therefore, the former suppliers of urban logistics, also including 4PL companies, can become customers of ULS.
- (iii) The consumers of ULS, in theory, include all those in the city who demand freight activities with goods matching the ULS load requirements. The types of services cover all types of urban logistics supply chains, including bulk cargo, wholesale and retail, and even former urban logistics supply services.

Note that ULS has an independent operator to manage both platform systems. Distinguished from traditional SSC, the most distinctive feature of the ULS-SSC is that

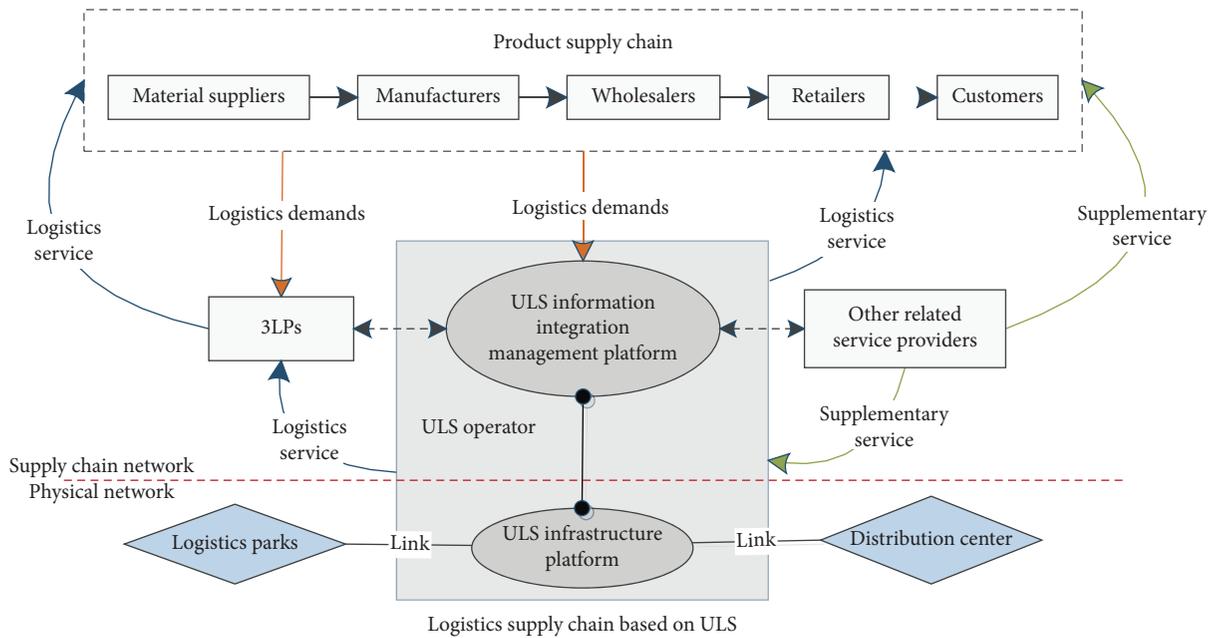


FIGURE 3: The structure of ULS-SSC.

the ULS operator acts as the logistics service integrator, unifying the management of the ULS infrastructure and third-party logistics as functional logistics service providers.

**3.3. Relationship between ULS and 3PLs in ULS-SSC.** The competitive and cooperative relationship between the ULS operator and 3PLs is central to the evolution of the supply chain. Figure 4 illustrates the gradual increase in the market share of ULS-SSC as the network density increases. The same trend is shown in the terminal distribution segment, but the necessity of ground-underground cooperation makes ULS a relatively low substitute.

While the expansion of ULS-SSC market share may have been initially led or driven by the government, the increase in network density has allowed ULS to become progressively more dominant and thus able to proactively attract customers [3]. In this process, the role of 3PLs in the supply chain gradually changes from being suppliers to buyers of transportation services.

Terminal distribution, as described above, can be implemented in a variety of ways, almost all of which require cooperation with ground distribution, which may be provided by 3PLs. Especially in the early stages of ULS network development, terminal distribution still relies on ground-based methods, as shown in Figure 4. Therefore, the joint distribution function (in Figure 5) needs to be added within the integrated information management platform in order to effectively integrate the logistics, information flow, and capital flow of the cooperating parties.

ULS terminal replaces the scattered logistics distribution points and centralizes the distribution and collection of orders. In addition, whether the final delivery is

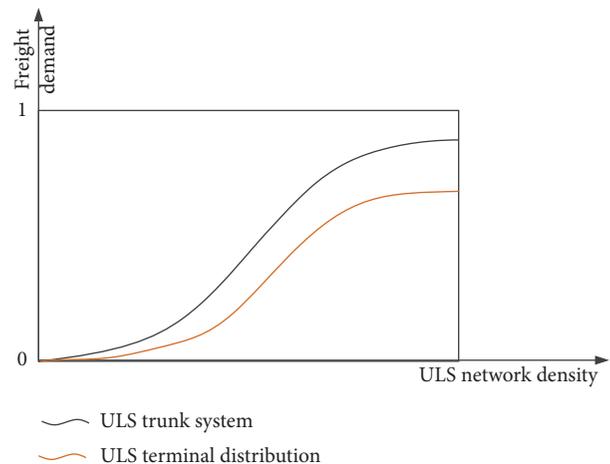


FIGURE 4: The market share changing of ULS.

done by ULS or other distribution providers, it can effectively respond to the brand promotion needs of logistics companies that need to face customers directly. For example, JD logistics (JDL) always wants customers to feel JDL's services, including parcels printed with JDL's logo or delivered by JDL's delivery agents to strengthen the brand image.

**3.4. ULS Service Mode.** ULS-SSC can provide personalized services for orders with different requirements. Considering the full utilization of resources and flexible operation, outsourcing services based on some links of the ULS system operation process is able to form a variety of service models. Available transportation services were divided into point-to-point mode and distribution mode.

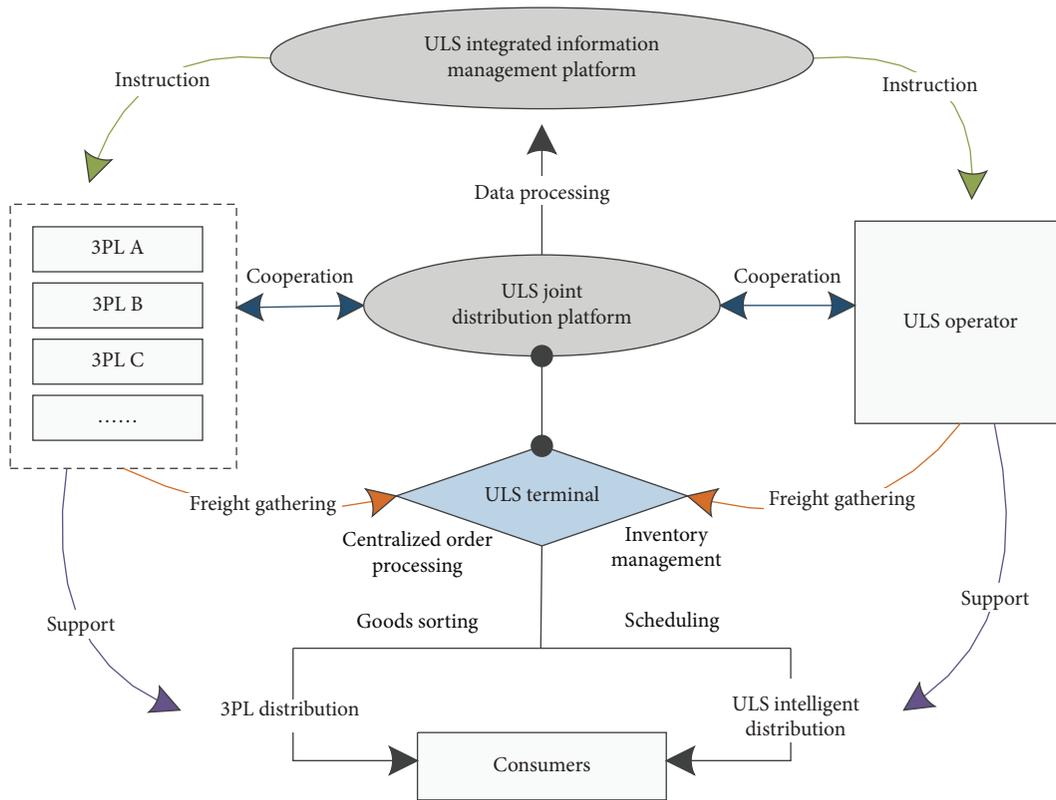


FIGURE 5: The terminal distribution mode flowchart.

3.4.1. Transportation Service

(1) *Point-to-Point Mode.* The point-to-point service mode is mainly for a high and stable flow of freight needs, such as bulk cargo supply, which can develop a long-term and stable order pattern. Moreover, such orders are usually sent from logistics parks or transportation hubs to in-town facilities with warehousing functions and can take full advantage of the convenience and savings of the ULS network, as the cargo flow paths fit perfectly with the layout of the ULS network.

(2) *Distribution Mode.* Express parcel distribution with large volumes, multiple and scattered destinations is the fastest-growing and most popular mode of urban logistics, which shows an annual growth rate of 20% in China. Express parcel distribution usually has high timeliness requirements and is closely related to people’s lives. A multilevel ULS network can efficiently realize the complex scheduling of such cargo transportation in transshipment and temporary storage.

3.4.2. *Outsourcing Service.* The implementation and links in the ULS-SSC system that can operate independently, such as transportation lines, nodes, and warehouses, can be outsourced to others, and the outsourcing service model is shown in Figure 6. With the ability to provide customized transportation services to specific regions or specific customers, outsourcing has the advantage that contracted operators will be able to respond quickly to orders with special

needs and will be able to utilize system resources for flexible pricing and facility operations. However, the overall operation of the supply chain is still unified by the integrated information management platform, including the information processing of orders, network dispatching, emergency response, and other implementation processes, as well as the collaboration of all outsourcing mode operators.

4. Process Design of ULS-SSC

Based on Zurawski and Zhou [49], the ULS-SSC was divided into three steps: (1) functional analysis of ULS-SSC, (2) subsystem design based on functional decomposition, and (3) the operation process design of ULS-SSC based on HCPN.

4.1. *ULS-SSC Functional System Analysis.* According to the structure and characteristics of the ULS-SSC, the supply chain functional structure (see Figure 7) containing four levels was proposed for SSC process design as follows:

- (i) Business layer: the main task is to manage the business relationships of the supply chain participants, including order processing (ULS with consumers), coordination management (ULS with other partners or providers), and financial management (ULS with banks and administration)
- (ii) Environment layer: it collects various information within the system, such as order requirements,

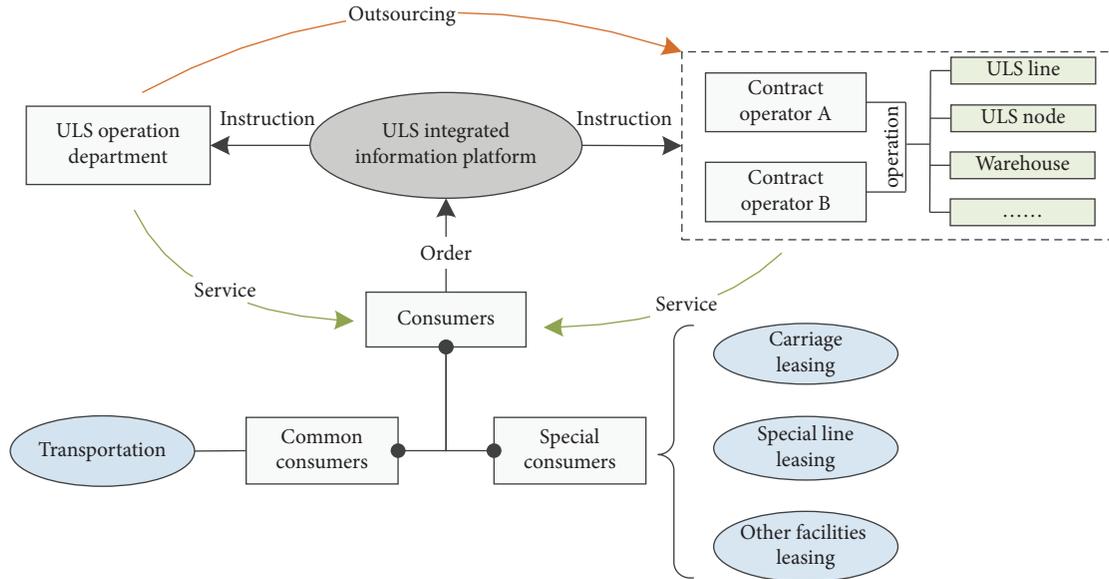


FIGURE 6: The outsourcing service mode of ULS.

resource quantities, and network status, and transmits the information to the control layer to serve the intelligent information management platform of ULS-SSC

- (iii) Control layer: it monitors system processes and system status in real-time, analyze data from the environment layer, and issue instructions to other subsystems to ensure proper system operation
- (iv) Operational layer: it receives instructions and completes the transportation process, including inventory management, circulation processing management, vehicle scheduling, and terminal distribution

- (iv) Pickup: after receiving the instruction, complete the pickup and perform the inspection.
- (v) Warehouse: ULS network node provides temporary warehousing and real-time monitoring for cargo to be processed or transhipped.
- (vi) Circulation processing: goods can be unpacked, sorted, repackaged, and other distribution processing activities within the ULS network node.
- (vii) Transportation: deliver goods as directed and optimize the transportation process, determine transshipment, and temporary storage solutions.
- (viii) Terminal distribution: complete the final part of the transportation and delivery to the customer.

4.2. *Subsystems.* Figure 8 describes the entire process of goods from placing an order to terminal delivery. The process shows the logistics, information, and capital flows between the eight subsystems. Each subsystem was described as follows:

- (i) Demand management: classify and generate orders by freight quantity, destination, type, or time.
- (ii) Information management: collect and process information, such as order processing, AGV loading and equipment status and then issue instructions.
- (iii) Finance management: process the prepayment of orders and postreceipt audits. There are two payment methods: cash and telegraphic transfer (T/T).

4.3. *HCPN Modelling.* We utilize CPN Tools version 4.0.1 to design the HCPN top model of the none-closed ULS-SSC process, as shown in Figure 9, as well as the Places and Transitions in Table 1. Eight subsystems in the ULS-SSC functional system were defined as subnets in the HCPN model. The setting into a none-closed model is due to the fact that it is easier to identify the state of the subsystems and the logical relationships between the subsystems under the independent order run simulation, so that it is also easier to perform the comparison of the system operation efficiency under different order types.

The HCPN is defined as a tuple  $HCPN = (S, SN, SA, PN, PT, PA, FS, FT, PP)$ . Here, the following are observed:

- (1)  $S$  is a finite set of subpages such that each subpage  $s \in S$  is a nonhierarchical CPN as follows:

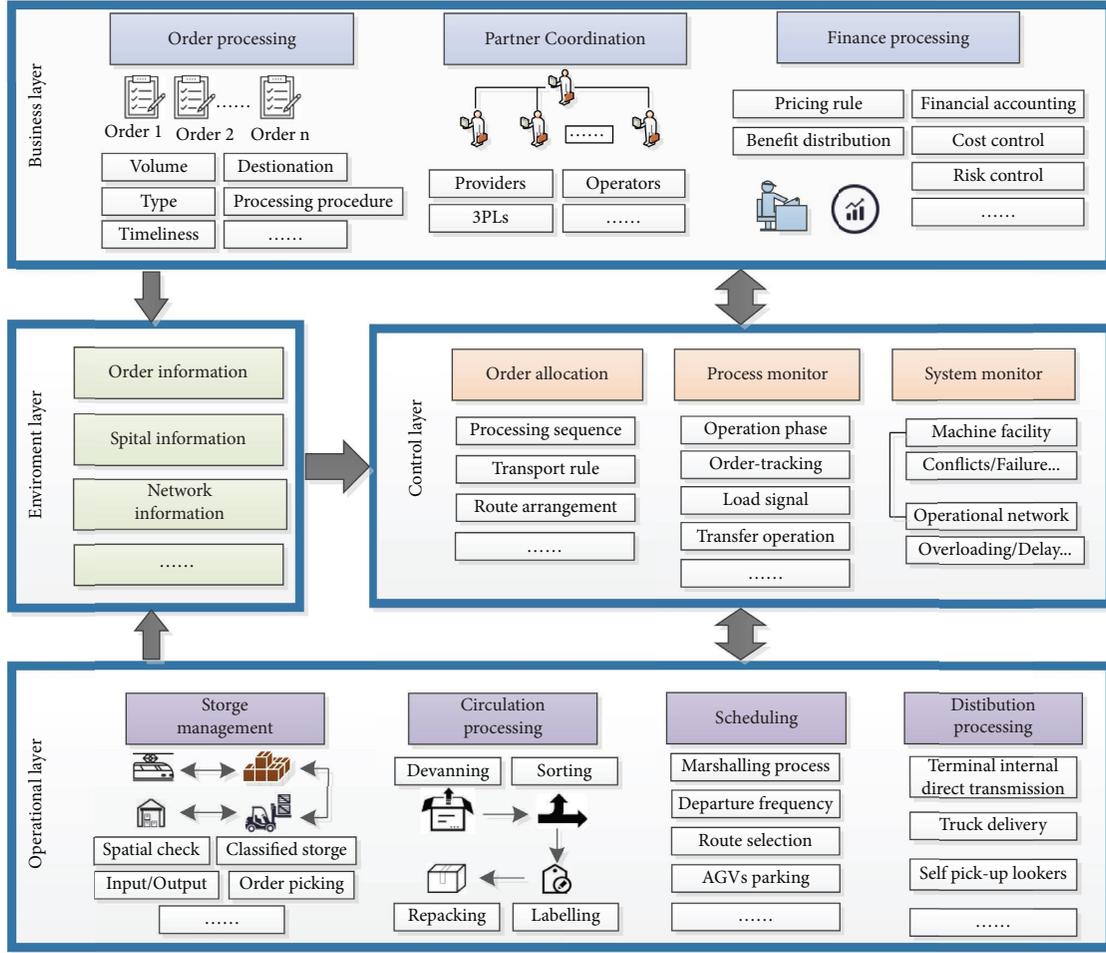


FIGURE 7: The functional structure of the ULS.

$$CPN = \left( \sum s, P_s, T_s, N_s, A_s, C_s, G_s, E_s, I_s \right),$$

$$\forall s_1, s_2 \in S: s_1 \neq s_2 \Rightarrow (P_{s_1} \cup T_{s_1}) \cup A_{s_1} \cap ((P_{s_2} \cup T_{s_2}) \cup A_{s_2}) = \emptyset. \quad (1)$$

- (2) SN is a set of substitution nodes of the HCPN model.
- (3) SA is a set of functions for substitution nodes to page S.
- (4) PN is a set of port nodes.

- (5) PT is the type function of PN and defined from PN to {in, out, i/o, general}.
- (6) PA is a port assignment function.
- (7) FS is a finite set of fusion sets, subject to as follows:

$$\forall f_s \in FS, \forall s_1, s_2 \in f_s: [C(s_1) = C(s_2) \wedge (I(s_1) = I(s_2))]. \quad (2)$$

- (8) FT is a fusion-type function.
- (9) PP is a multiset of prime pages.

When receiving the freight order, the information of the order is transited to *Demand Management*. The confirmed order type (whether the order needs circulation processing) information is posted to *Information Management*. Meanwhile, *Finance Management* confirms the prepayment status and then sends it to *Information Management*. Next,

*Information Management* issues order processing instructions for *Pickup* or *Transportation* based on ULS system resources and equipment status. After receiving the instruction, *Pickup* arranges vehicles to pick up cargo and move to the storage yard in the ULS node. Afterward, warehousing (in *Warehouse*), circulation processing (in *Circulation Processing*), and transportation operations (in *Transportation*) are performed in sequence. During transportation, goods arrive at any node to be identified and

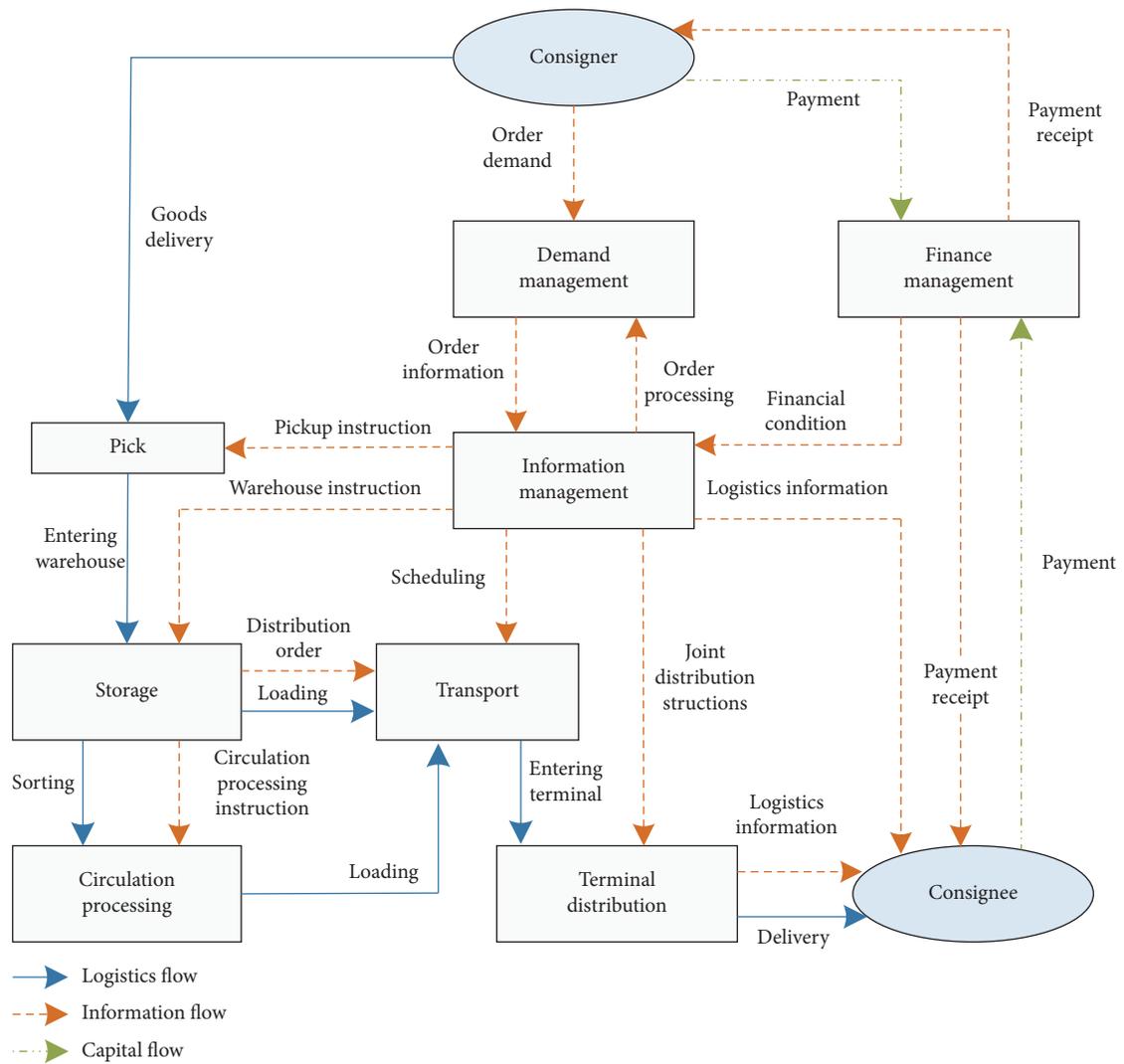


FIGURE 8: The relationship between subsystems.

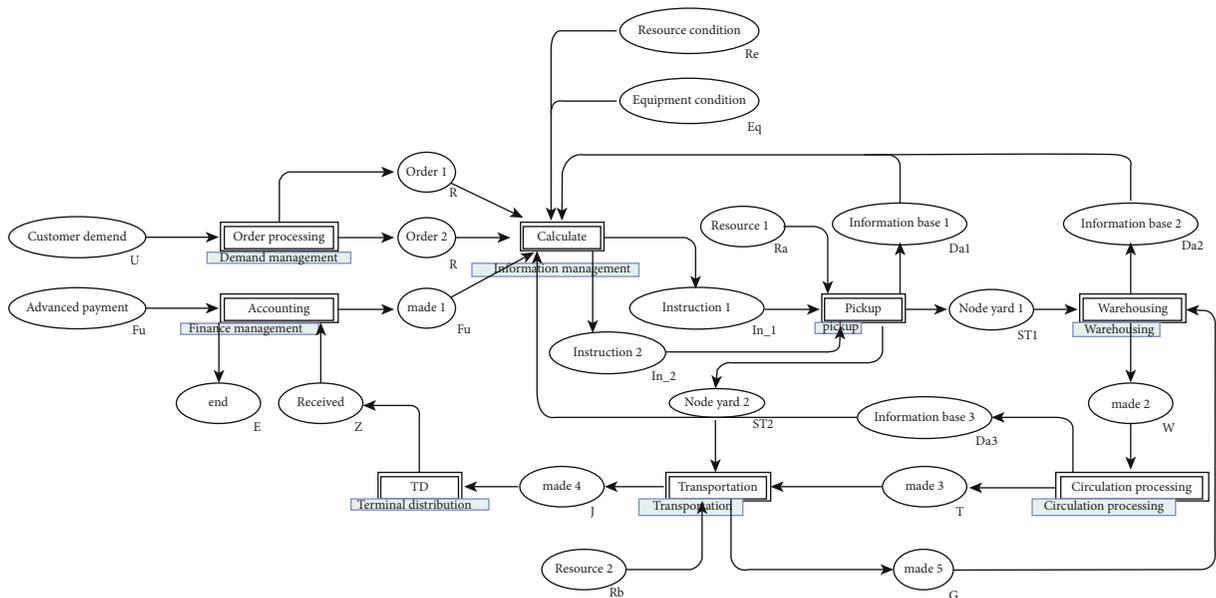


FIGURE 9: The HCPN top model of ULS-SSC.

TABLE 1: ULS-SSC top layer places and transitions description.

| Place                  | Description   | Transition             | Description                     |
|------------------------|---|------------------------|---------------------------------|
| Customer demand        | Customer freight demand                             | Order processing       | Demand management               |
| Order 1,2              | Order type  | Calculate              | Information management          |
| Made 1,2,3,4,5         | Information output                                  | Pickup                 | The process of picking up goods |
| Instruction 1,2        | Instruction issued by the control center            | Warehousing            | Process of warehousing          |
| Information base 1,2,3 | Information collector                               | Circulation processing | Circulation processing          |
| ULS node               | Station of ULS where can operate functional process | Transportation         | Process of ULS transportation   |
| Received               | Consignee completes the goods receipt               | Terminal distribution  | Terminal distribution           |
| End                    | The order finished                                  | Accounting             | Finance management              |
| Resource 1,2           | System repository                                   |                        |                                 |
| Resource condition     | Resource utilization of subsystem                   |                        |                                 |
| Equipment condition    | System equipment status                             |                        |                                 |

manipulated for unloading, transfer, or storage. Finally, delivery is completed by *Terminal Distribution* and fed back to *Finance Management* to confirm order completion, which takes into account the timeliness of the three terminal distribution methods.

Figures 10(a)–10(h) illustrates the subsystem models corresponding to the substitution transitions in the HCPN top model, respectively. The subsystems portray in detail the full process operation flow of the token from entering to leaving the subsystem, where the token represents the resources within the system.

## 5. Data Analysis and Discussion

**5.1. Model Validation.** Two types of orders based on whether the circulation processing is required were designed in the HCPN model. P-type orders require circulation processing, while Q-type orders do not and go directly to the transportation subsystem. P-type and Q-type orders represent two typical freight requirements for urban logistics: *distribution mode* and *point-to-point mode*, respectively. For example, in Figure 10(g), a P-type order requires an additional storage judgment (short for S-Judge) at each node, while a Q-type order only makes a judgment (T-Judge) about whether it has reached its destination. Therefore, Q-type orders are more time-sensitive.

Table 2 lists the simulation parameter settings, which were obtained by investigating the actual operation data of current logistics management systems of large logistics companies, such as JD Logistics, and combining them with the relevant literature of ULS.

The set HCPN model is valid as evidenced by three characteristics: (1) Seven dead markings exist, which represent the markings at the end of the model run due to the nonclosed-loop structure. The remaining markings are all alive, in line with the initial design intent of the model. (2) There is no dead transition instance, i.e., there is no deadlock in the model due to the inactivation of transitions. (3) There is no live transition instance, i.e., the model will not be trapped in a local infinite loop. Monitors were set up at key transitions to observe the system operational conditions. Table 3 statistics the model performance results under 1000 simulations for each of the two order types. The average total running time of P-type and Q-type is 77.50 and 61.55

minutes, respectively. The reason some monitors have more or less than 1,000 is that an order may go through transit, warehousing, multiple times, or may avoid a particular process.

**5.2. The Role of the Integrated Information Management Platform.** The effectiveness of the HCPN model likewise indicates the rationality and feasibility of the set integrated information management platform in terms of process disposition and functional design. The platform can promote value cocreation and optimize the competitive and cooperative relationships among participants in the supply chain. Therefore, taking into account the infrastructure properties of ULS, the proposed value of the supply chain based on the platform operation needs to be measured comprehensively in terms of the effectiveness of the urban logistics system, the distribution of benefits among subjects, and the external benefits of SSC.

The phased development of the information platform formed based on the ULS network around the realization of the proposed value of the supply chain is also accompanied by changes in the roles of the participants (3PLs/4PLs) and the emergence of new cooperation mechanisms. In the initial stage of the ULS network, the platform-led supply chain activities mainly serve the simple order mode, such as the point-to-point mode. The development of the platform needs to focus on the openness of the SSC system and the increase of social participation. As the network grows, the increase in the number and variety of orders prompt more partners to join the SSC operation and develop multiple service modes. At this stage, platform development requires continuous optimization of service modes and supply chain resources, especially reducing the flow delay of supply chain links to improve efficiency, thus attracting more participants until the formation of a stable, multiservice model synergistic ULS-SSC.

**5.3. Efficiency Improvement of ULS-SSC.** Supply chain efficiency improvement is an important criterion for technological innovation. Although there is no experiment comparing the efficiency of ULS-SSC and traditional urban logistics SSC in this paper, the simulation results in the new supply chain model suggest the key aspects of urban logistics

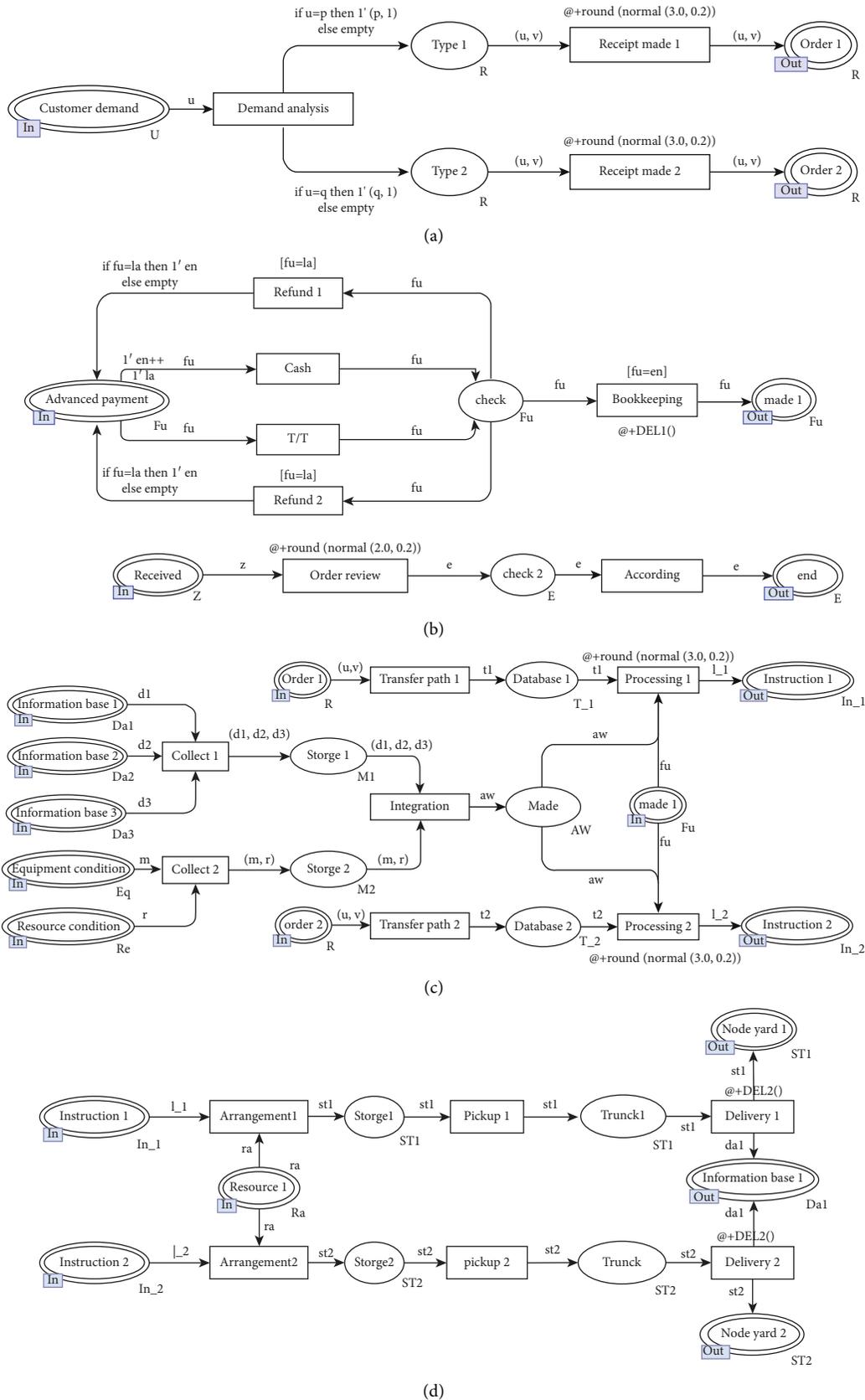


FIGURE 10: Continued.

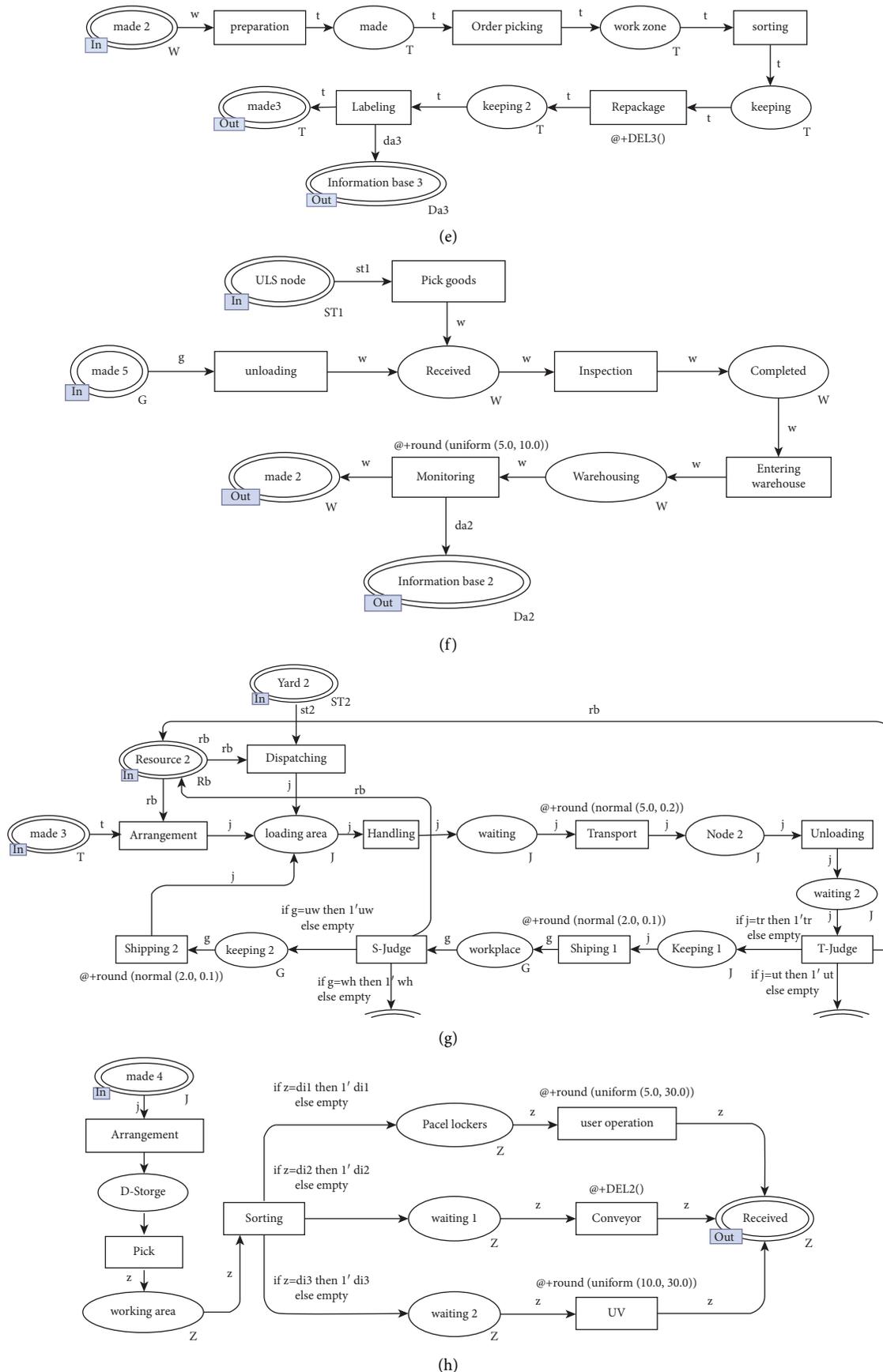


FIGURE 10: The subsystem models of ULS-SSC. (a) Demand management, (b) finance management, (c) information management, (d) pickup, (e) circulation processing, (f) warehousing, (g) transportation, and (h) terminal distribution.

TABLE 2: Parameter setting.

| Process                | Operating time (min) | Operational cost (yuan/min) |
|------------------------|----------------------|-----------------------------|
| Demand management      | (1–5)                | 0.02                        |
| Bookkeeping            | (1–5)                | 0.01                        |
| Information process    | (1–5)                | 0.04                        |
| Pickup                 | (10–30)              | 0.04                        |
| Warehousing            | (5–10)               | 0.08                        |
| Circulation processing | (5–10)               | 0.06                        |
| Transportation         | (3–7) in each node   | 0.06                        |
| Transshipment          | (1–4)                | 0.08                        |
| 3PL distribution       | (5–30)               | 0.10                        |
| Conveyor belts         | (10–30)              | 0.08                        |
| Unmanned vehicles      | (10–30)              | 0.06                        |
| Order review           | (1–4)                | 0.02                        |

TABLE 3: ULS-SSC HCPN model simulation results.

| Order type            | Monitor Subsystem      | Name                   | Count          | Average time delay | Proportion (time) (%) | Average operational cost | Proportion (cost) (%) |
|-----------------------|------------------------|------------------------|----------------|--------------------|-----------------------|--------------------------|-----------------------|
| P                     | Demand management      | Receipt Made 1         | 1000           | 3.00               | 3.57                  | 0.0600                   | 1.23                  |
|                       |                        | Bookkeeping            | 1000           | 3.01               | 3.58                  | 0.0301                   | 0.62                  |
|                       | Finance management     | Order review           | 1000           | 1.98               | 2.36                  | 0.0396                   | 0.81                  |
|                       |                        | Information management | Processing 1   | 1000               | 3.01                  | 3.58                     | 0.1204                |
|                       | Pickup                 | Delivery               | 1000           | 20.05              | 23.86                 | 1.0025                   | 16.50                 |
|                       | Circulation processing | Repackage              | 1475           | 11.14              | 13.26                 | 0.6684                   | 13.75                 |
|                       | Warehousing            | Monitoring             | 1475           | 10.99              | 13.08                 | 0.8792                   | 18.09                 |
|                       |                        | Transport              | 1945           | 9.74               | 11.59                 | 0.5844                   | 12.03                 |
|                       | Transportation         | Shipping 1             | 945            | 0.98               | 1.17                  | 0.0784                   | 1.61                  |
|                       |                        | Shipping 2             | 470            | 0.66               | 0.79                  | 0.0528                   | 1.09                  |
|                       | Terminal distribution  | 3PLs delivery          | 328            | 5.90               | 7.02                  | 0.5900                   | 12.14                 |
|                       |                        | Conveyor               | 347            | 7.04               | 8.38                  | 0.5632                   | 11.59                 |
|                       |                        | UV                     | 325            | 6.52               | 7.76                  | 0.3912                   | 8.05                  |
|                       | Q                      | Demand management      | Receipt Made 2 | 1000               | 2.98                  | 4.84                     | 0.0596                |
| Bookkeeping           |                        |                        | 1000           | 2.95               | 4.79                  | 0.0295                   | 0.90                  |
| Finance management    |                        | Order review           | 1000           | 2.01               | 3.27                  | 0.0402                   | 1.22                  |
|                       |                        | Information management | Processing 2   | 1000               | 3.01                  | 4.89                     | 0.1204                |
| Pickup                |                        | Delivery               | 1000           | 19.99              | 32.48                 | 0.7996                   | 24.30                 |
|                       |                        | Transport              | 1953           | 9.75               | 15.84                 | 0.585                    | 17.78                 |
| Transportation        |                        | Shipping1              | 953            | 0.93               | 1.51                  | 0.0744                   | 2.26                  |
|                       |                        | Shipping2              | 953            | 0.94               | 1.53                  | 0.0752                   | 2.29                  |
|                       |                        | 3PLs delivery          | 334            | 5.70               | 9.26                  | 0.5700                   | 17.32                 |
| Terminal distribution |                        | Conveyor               | 347            | 6.96               | 11.31                 | 0.5568                   | 16.92                 |
|                       |                        | UV                     | 319            | 6.33               | 10.28                 | 0.3798                   | 11.54                 |

efficiency improvement. Throughout the supply chain process, pickup, circulation processing, and warehousing of P-type orders take up most of the time during the ULS operation, with the average time delays accounting for 23.86%, 13.26%, and 13.08%, respectively. The terminal distribution process also takes a lot of time, with the percentage of time spent in both types being about 30%. Pickup takes 32.48% of the time in Q-type. The average delay in the transportation link is related to the distance travelled and is about equal for both types, at 13.55% and 18.88%,

respectively. The longer average delay for P-type is mainly spent on intrasystem transshipments and temporary warehousing. The three terminal distribution modes are adopted with approximately equal frequency. In addition, except for the transportation subsystem, other aspects such as information management and transshipment take less time.

Technically, circulation processing and warehousing can be improved by increasing the intelligence level of system equipment. Moreover, if a closed model is further constructed, it will be able to reflect the flow of resources in the

supply chain and thus carry out systematic optimization of the efficiency of the operational process.

From the perspective of supply chain collaboration, the data results show that the time spent on pickup and terminal distribution together is extremely high, about 50% and 60% under P-type and Q-type orders, respectively. Apart from the inevitable waiting time in the pickup segment, the huge time consumption is firstly because the combined delivery of orders was not considered in the model, i.e., the goods were set to have no waiting time at the end station, and secondly because there is only one partner for each process under a single run. However, with the expansion of the network scale and supply chain cooperation scale, a multitype cooperation mode in the front end will enrich the order acquisition channel and enhance the speed of pickup, and at the end, joint distribution based on resource integration will also reduce the average distribution time of a single piece of goods. Moreover, the intelligent deployment at the end of the ULS infrastructure network can further enhance pickup and distribution efficiency.

**5.4. Operational Cost Analysis of ULS-SSC.** The operational cost of ULS is crucial to compete with traditional logistics services. Current urban logistics is still a labor-intensive industry and fragmented orders make it challenging to integrate and optimize logistics processes, while unmanned and integrated management is both unique advantages of ULS. Simulation results indicate that the cost of processes requiring manual operation accounts for a larger proportion of total costs, such as pickup (16.50% and 24.30% for P-type and Q-type, respectively) and terminal distribution (31.78% and 45.79% for P-type and Q-type respectively), whereas the cost of fully automated transportation is relatively low. Compared to Q-type orders, circulation processing and warehousing make for a significant increase in operational cost for P-type orders. Particularly, the limited storage capacity and high management fees at ULS nodes make warehousing cost substantial (18.09%) of the total supply chain cost.

The integration of supply chain resources contributes to a further reduction in system operational cost. By pooling multiple types of logistics orders and carrying out a series of logistics links in the system, ULS avoids the increased unit costs of a small number of frequent logistics orders and the time wastage caused by fragmented processes. In addition, collaborative operations of supply chain participants can reduce average logistics costs, share operational risks, and improve overall supply chain efficiency as well as resilience.

**5.5. Supply Chain Operations Based on ULS Network Development.** The ULS network is the physical carrier of the new urban logistics supply chain system. The development process of the network has a significant impact on the formation and operation of the ULS-SSC.

As a new class of underground infrastructure, ULS networks that can generate scale effects have large investments and long construction cycles. Although local

governments usually lead the initial investment in such infrastructure projects with large social benefits, the benefits of prioritized routes in the ULS network greatly influence the confidence of the logistics market in the innovative model. Good initial benefits can accelerate the formation of the network and can also attract supply chain partners to develop a willingness to cooperate earlier, or even directly participate in the investment and construction.

Accordingly, in the initial stage when the network coverage is not high, the initial route selection and planning is oriented to Q-type order paths as much as possible to ensure the economy of ULS-SSC. Subsequently, the distribution model (P-type), which requires greater network coverage, is gradually carried out.

Finally, it is worth also noting that obtaining the support of local governments, both in terms of investment and policy, is crucial to the realization of ULS-SSC. Although, as a logistics system, economic benefits are paramount, local governments are more concerned with social benefits and urban sustainability resulting from innovation. Admittedly, ULS itself is a green logistics method, energy saving, and low carbon are still important process optimization goals in ULS-SSC operations. In this way, it is more beneficial to cooperate with local governments to develop appropriate policies to encourage the development of ULS. In this way, the development of ULS can fit in with the policy of greening and reducing emissions, as well as enhancing the willingness of local governments to provide subsidies and tax breaks for green logistics operations.

## 6. Conclusions

With the aim of promoting the integrated management and efficiency of urban logistics, an intelligent logistics management platform based on the new infrastructure of ULS can gradually lead to the evolution of the logistics market and the formation of a new urban logistics services supply chain mode. The current work, first, analyzed the process of market evolution characterized by a shift in the role of logistics supply chain participants and constructed a preliminary framework for ULS-SSC comprising four aspects: physical network, structure, relationship, and service mode. Second, based on the ULS-SSC functional system analysis and the operational relationships between the decomposed subsystems, the CPN tools were adopted to construct an HCPN model that can effectively express the hierarchical organizational structure and operational processes of ULS-SSC. Then, an example containing two order types was designed to validate the model, where orders were classified into P-type and Q-type according to whether the circulation processing is required, corresponding, respectively, to *distribution mode* and *point-to-point mode*.

The results show the importance of the integrated information management platform in supply chain operations and demonstrate that manual involvement in logistics is an influential factor in supply chain operation time and cost and that links with initial pickup and terminal distribution can be improved by extending the

ULS network upstream and downstream or by outsourcing services and supply chain synergies. Within the ULS, intermediate links with high-time delays can be improved by optimizing the ULS technology system, as well as optimizing the scheduling with a more rational order allocation to reduce the efficiency and costs associated with resource congestion in circulation processing or warehousing. The findings reflect that compared to road-based logistics SSC, the automated networked operation and integrated management of multiple urban supply chains by ULS-SSC offers a revolutionary innovation in urban logistics SSC, providing a sustainable development direction for the urban logistics SSC.

This work develops theories related to the operation of ULS-SSC, and the proposed ULS-SSC model extends the operational process of SSC to ground-underground integration. It fills a gap in the ULS body of knowledge on market operations, which is currently dominated by the study of transport technology, network design, and single-route operational processes. The designed ULS-SSC HCPN model can be used as one of the theoretical bases for the application of the new transport technology ULS and contributes to further research on the ULS operational model and the synergistic relationships of the participants, thus deepening the acceptance of the feasibility of implementing the ULS in the transport market.

Limitations are inevitable, given that this work is an early study of the integration of ULS with urban logistics supply chains. Firstly, the constructed nonclosed HCPN model can already clearly describe the state of the system under a single run, providing a basis for further construction of closed models to simulate resource cycles and system optimization. Secondly, the diversity and complexity of the supply chain in the actual urban logistics system have been simplified, with only two order types simulated and the running time of each link set in a simplified manner. Based on the current work, the collaboration mechanism of the ULS operational participants can be studied in the future by analyzing their positioning in the ULS-SSC. Furthermore, the ULS-SSC operation mode under the convergence of multiurban logistics order types, as well as cost sharing and pricing could be investigated.

## Data Availability

The data used in this model are from online open sources and expert consultation.

## Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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