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Article

Modeling for underground logistics system in the Korean metropolitan area

Uri Chae[1], Gihyun Lee[2], Austin Kang[3,*], Joo Uk Kim[1,*]

[1] Innovative Transportation and Logistics Research Center, Korea Railroad Research Institute, Uiwang-si 16105, Republic of Korea
[2] Korea National Industrial Convergence Center, Korea Institute of Industrial Technology, Cheonan-si 31001, Republic of Korea
[3] Department of Medicine, Seoul National University, Seoul 30380, Republic of Korea
*** Corresponding authors:** Austin Kang, animus70@snu.ac.kr; Joo Uk Kim, jookim@krri.re.kr

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Abstract: This study evaluated the development and validation of an integrated operational model for the Underground Logistics System (ULS) in South Korea's metropolitan area, aiming to address challenges in urban logistics and freight transportation by highlighting the potential of innovative logistics systems that utilize underground spaces. This study used conceptual modeling to define the core concepts of ULS and explored the system architecture, including cargo handling, transportation, operations and control systems, as well as the roles of cargo crews and train drivers. The ULS operational scenarios were verified through model simulation, incorporating both logical and temporal analyses. The simulation outcomes affirm the model's logical coherence and precision, emphasizing ULS's pivotal role in boosting logistics efficiency. Thus, ULS systems in Korea offer prospects for elevating national competitiveness and spurring urban growth, underscoring the merits of ULS in navigating contemporary urban challenges and championing sustainability.

Keywords: underground logistics system; urban logistics; freight transportation; metropolitan area; sustainable logistics

1. Introduction

Managing the constant movement of goods and products is essential in modern cities for maintaining a sustainable logistics system (Galkin, 2017). There is a growing trend to creatively utilize underground spaces to enhance urban logistics systems. These efforts are not limited to passenger transportation but also include innovative concepts for freight transport, aiming to revolutionize the city's logistics landscape (Hu et al., 2019). The Underground Logistics System (ULS), which uses underground tunnels and networks, offers an efficient approach to urban logistics and freight transportation (Hai et al., 2020). ULS has emerged as a solution to traffic congestion and environmental pollution issues plaguing many cities (Dong et al., 2018). Since the 1990s, ULS has garnered attention globally, with studies conducted in the United States (Rezaie et al., 2016), Germany (Stein, 2003), the Netherlands (Wiegmans et al., 2010), and Japan (Taniguchi, 2002). However, challenges like integration with urban infrastructure, ensuring safety and efficiency, among others, persist (Guo et al., 2021; Zheng et al., 2021). Wiegmans et al. (2010) noted that ULS in the Netherlands, despite a decade of implementation, faced challenges such as unclear operational goals, high costs, and limited logistics hubs. Guo et al. (2021) underscored the need for demand forecasting of logistics flows and an integrated ULS network that aligns with existing infrastructure. Previous research has mostly concentrated on network planning (Zheng et al., 2021) and feasibility assessments (Chen et al., 2018; Pietrzak et al., 2021). Hu et al. (2023) evaluated the metro-based underground logistics system (M-ULS) in megacities, emphasizing its sustainable features. Their study employed a two-tier M-ULS network based on a satellite city project in Beijing, a context distinct from the subway systems in Korea. Roodt et al. (2020) delved into Sydney's heavy-rail signaling and control systems, highlighting the adoption of Systems Engineering. While their insights are valuable, direct application to South Korea's metropolitan subway network ULS might be challenging. Despite these advancements in ULS research globally, there is a notable lack of analysis and modeling of ULS in South Korea. This gap indicates the need for comprehensive studies to understand and develop ULS models tailored to the unique urban logistics challenges in South Korea. Thus, this study proposed an integrated operational model for ULS in South Korea's metropolitan area, aiming to bolster urban logistics. By presenting conceptual modeling, this research seeks to identify and resolve issues proactively during system development. As cases where operational concepts are used for modeling before system development increase (Fan et al., 2020), such methodologies can clarify system functionality and reduce risks. This study aimed to address several key research questions related to the development and integration of ULS in South Korea's metropolitan areas. Research questions are as follows. First, how can an integrated ULS model for South Korea's metropolitan areas improve urban logistics efficiency, reduce traffic congestion, and mitigate environmental concerns? Second, what are the key components and operational aspects that need to be simulated and integrated to ensure the successful implementation of ULS, and how can temporal and logical analyses optimize its performance? Third, what challenges exist in adapting global ULS models to South Korea's urban infrastructure, and how can issues such as high costs and security risks be addressed to ensure the system's effectiveness? This study is structured as follows: Section 2 provides an overview of the methods used to develop the integrated ULS model, including the review of related systems and the detailed description of the operational scenario model. Section 3 presents the results of the analysis, highlighting key findings from the proposed model. Finally, Section 4 discusses the implications of these findings for urban logistics in South Korea, concluding with suggestions for future research and the potential impact of ULS on the urban landscape.

2.Methods

2.1. Review of Integrated modeling

2.1.1. System structure

The ULS model proposed in this study integrates various systems and users that are essential for urban logistics operations. The model includes seven key components, which are cargo workers, Automated Guided Vehicles (AGVs), Vertical Transfer Systems (VTSs), operational systems, control systems, cargo crews, and freight train drivers. These components work together to ensure the efficient and seamless operation of the ULS, as illustrated in **Figure 1**.

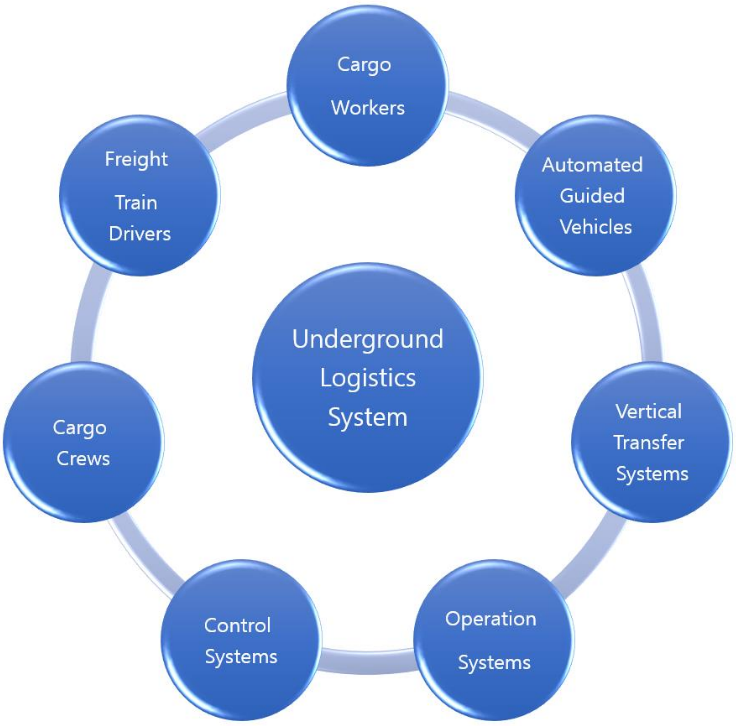

Figure 1. Structure of underground logistics system.

Cargo workers perform crucial tasks such as loading, storing, and unloading cargo, ensuring a smooth flow of goods within the logistics system. AGVs play a significant role in transporting cargo through underground tunnels, which enhances transportation efficiency and reduces traffic congestion. VTSs facilitate the transfer of cargo between different levels, promoting smooth operations within the system and maximizing space utilization. Operational systems oversee the logistics flow, track cargo, and provide real-time location updates to stakeholders, as well as monitor assets like parcel volume and standard roll containers. Control systems manage the functions of AGVs and VTSs, including calculating loading and unloading sequences for cargo trains and adjusting devices as needed. Cargo crews are responsible for loading, unloading, and safely handling cargo while also conducting maintenance, documentation, and inspections. Freight train drivers manage the operation of freight trains and ensure the efficient transfer of cargo.

Each component of the system plays a unique role in maintaining the overall efficiency of the ULS. **Figure 2** provides a detailed visualization of the system structure, showcasing the connections and processes involved.

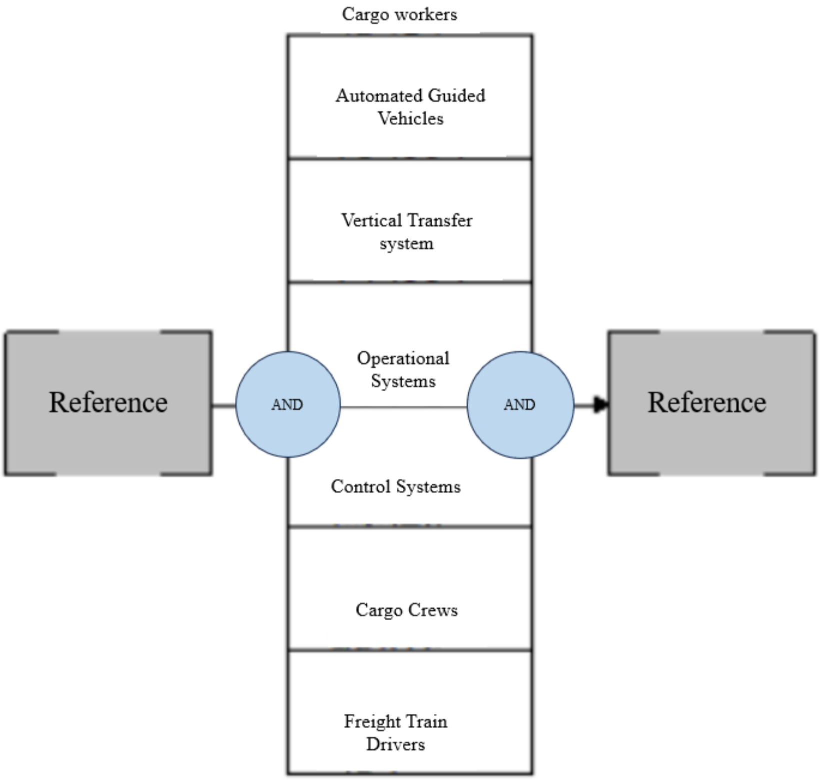

Figure 2. Example of system structure.

2.2. Detailed modeling

Modeling is the process of visually representing content from texts or documents using specific symbols or notations (Cichocki et al., 2022). Logistics network modeling, however, involves analyzing factors such as a company's logistics network costs, hub locations, capacity, and transportation routes. This process entails both modeling and performing simulations (Bing et al., 2014). ULS scenarios detail the system's functions over time and represent items between functions sequentially. These details can be directly incorporated into the modeling process (Prashanth et al., 2021). The modeling process can either begin with creating a single integrated model that is later decomposed into detailed models, or by developing detailed models first, followed by the construction of an integrated model. Detailed models further break down into freight transportation operation scenarios and retrieval transportation operation scenarios. These models pertain to the transportation of cargo to terminals or the transportation of retrieved cargo to retrieval vehicle bases. While creating detailed models first can simplify the development of the integrated model, any subsequent modifications become cumbersome as both detailed and integrated models need concurrent adjustments. Conversely, starting with the integrated model might be intricate and time-intensive but can resolve most errors before decomposition, leading to fewer alterations. In this study, ULS operation scenarios were formulated post the creation of detailed scenarios. Hence, any adjustments mandated simultaneous modifications to both the detailed and integrated models. Both models were subsequently revised and refined. The integrated model encompasses both the freight transport operation and retrieval transport operation scenarios, as delineated in **Table 1**. The former includes steps like cargo loading, AGVs and freight transport of standard roll container connections, AGV groupings, freight monitoring, and cargo unloading. Similarly, the retrieval transport operation scenario encapsulates actions such as cargo loading, AGVs grouping, VTSs operation, and cargo unloading.

Table 1. Classification of integrated model.

Category	Scenario
Freight transport operation scenario model	Cargo loading AGVs and freight transport of standard roll container connection AGVs grouping Loading on AGVs Freight transport of standard roll container binding Freight transport monitoring AGVs unloading VTSs boarding VTSs operation AGVs and freight transport of standard roll container Connection release Cargo unloading
Retrieval transport operation scenario model	Cargo loading Freight transport of standard roll container connection AGVs grouping VTSs boarding VTSs operation AGVs loading Freight transport of standard roll container binding, Freight monitoring AGVs unloading Freight transport of standard roll container connection release Cargo unloading

2.3. Integrated model

The integrated model is developed by combining the various unit models within the ULS, ensuring each one is free of errors before integration. Problems that may not be detected in individual unit models often emerge when these models are combined into the larger integrated model. Therefore, the integrated model is constructed to identify and resolve such issues.

2.3.1. Freight transport operation scenario model

The freight transport operation scenario model outlines the steps involved in transporting cargo via AGVs and freight trains. Cargo is loaded into standard roll containers at the vehicle base logistics area, then moved and loaded onto freight trains, which are connected to AGVs. Once the cargo arrives at a freight station dump platform, the AGV unloads the cargo to the designated floor using a VTS. The freight transport model is divided into 11 detailed scenario models, incorporating 7 systems (users), 126 functions (activities), and 83 items.

The freight transport operation scenario model (**Figure 3**) is segmented by the flow into the vehicle base logistics area (which includes the vehicle base elevator platform), freight train, freight station stack platform (freight station elevator platform), and freight station logistics area. The reasons this study focuses on the freight transport operation scenario model are as follows: First, the freight transport operation scenario aids in optimizing the origin, destination, route, and scheduling of freight. This can enhance the efficiency of freight transport and conserve both time and energy by optimizing the movement of vehicles and trains. Second, the freight transport operation scenario can ascertain the most efficient way to organize and utilize facilities and transportation means such as freight stations, platforms, and bases. This reduces costs, minimizes resource wastage, and ensures a seamless logistics process. Third, the freight transport operation scenario can forecast freight demand and transport patterns, enabling transport planning and the formulation of strategies to adapt to evolving circumstances. Fourth, based on the transport scenario, a process for continuous monitoring and enhancement of transport performance can be established. Through this, transport quality and reliability can be bolstered.

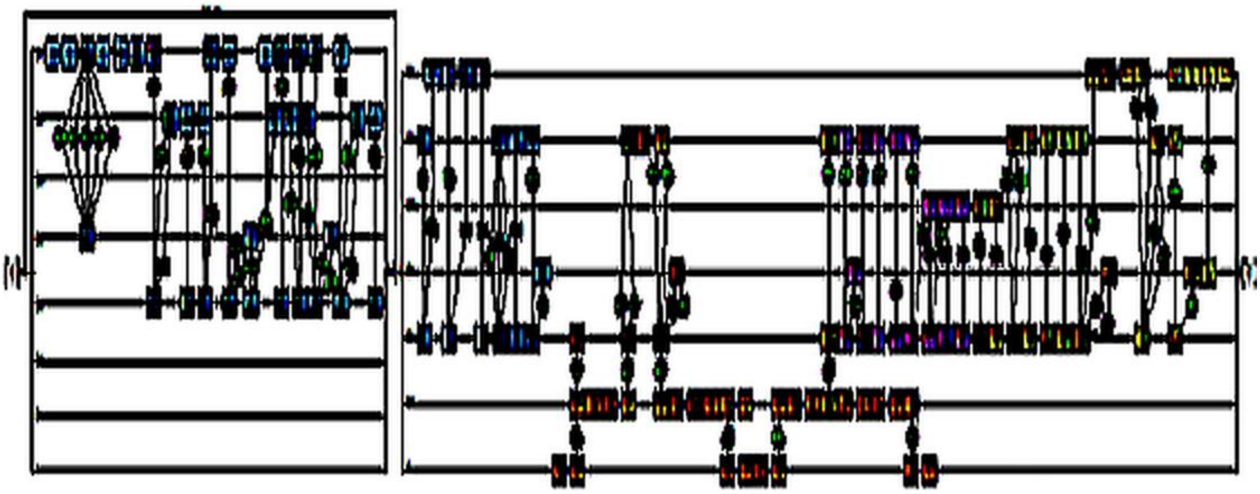

Figure 3. Freight transport operation scenario model.

The vehicle base logistics area is a space where cargo workers load goods into standard containers and connect them to AGVs and standard roll containers, forming grouped cargo. After grouping, the AGVs are positioned to await freight trains. Various operations and connections are executed within this logistics area to ensure an efficient and streamlined logistics process, guaranteeing the effective transportation of goods. Initially, goods are loaded and secured in this space, meaning cargo workers place the goods into standard roll containers. During this procedure, the goods are arranged stably within the containers to withstand movements and impacts during transport. These goods are then grouped by connecting the AGVs to the standard roll containers, completing the transport preparations. Subsequently, the goods are transferred to the freight train waiting area using AGVs. Once the cargo operations are finalized, the cargoes connected to the horizontal conveyance system are moved to the designated waiting area for freight trains. At this stage, the AGVs undergo preliminary preparations before loading the goods onto the freight trains.

The cargo train depot is a crucial component of urban logistics systems that utilize underground spaces for transporting cargo. This facility manages the boarding, transit, and unloading of AGVs connected to standard roll containers, which carry the cargo.

The connection between the standard roll container and the AGVs is established within the cargo train depot. Here, cargo is loaded into the roll container, which is then linked to the AGVs. This connection ensures cargo stability and facilitates movement within the transport apparatus. Additionally, this depot is the site for cargo transit and unloading. AGVs, tethered to the standard roll containers, safely transport the cargo within the train. Once the cargo is securely onboard the transport device and standard roll container, it journeys to its destination with stability. Upon reaching the destination, the transport device safely unloads the cargo. Efficient transportation management is another feature of the cargo train depot, incorporating devices designed for the streamlined handling of cargo. These mechanisms guarantee cargo safety and the smooth operation of the entire logistics system.

The freight station dummy platform, also known as the freight station platform, is a pivotal component of the urban logistics system that utilizes underground spaces. This platform is where AGVs, after disembarking from freight trains, use vertical transport devices to move cargo to its designated floor. Upon reaching the platform, AGVs transition to VTSs. Once an AGV has departed from the freight train, it navigates to the platform, connects to a vertical transport device, and securely boards it. The cargo is subsequently transported vertically to its destination floor. The VTS plays a vital role in facilitating the movement of cargo between different levels. After reaching the destination floor, AGVs proceed to the designated area for cargo unloading. Cargo workers then carefully unload the cargo, ensuring precision and safety throughout this step.

The freight station logistics area is another crucial component of the urban logistics system that makes use of underground space. In this area, AGVs, once unloaded from the freight train, navigate and disconnect from the standard roll containers. Cargo workers then safely unload the contents of these containers. After being unloaded from the freight train, the AGVs move to the freight station logistics area, where cargo workers disconnect the cargo from the roll containers. This process demands precision and safety. The freight station logistics area serves as the venue for cargo handling and unloading, where workers inspect the condition and safety of the cargo. The unloading process requires accuracy, speed, expertise, and attention to detail. This area is vital for efficient cargo handling and plays a key role in ensuring the logistics system’s effectiveness and safety. Activities here must be executed promptly and precisely to ensure a seamless transition to the next phase of transportation via vertical transport devices. Therefore, the proficient operation of the freight station logistics area is imperative for the smooth functioning of the entire logistics system and the successful transport of cargo.

2.3.2. Retrieval logistics operation scenario model

The retrieval transportation operation scenario model (**Figure 4**) is pivotal for seamlessly connecting and efficiently operating the various components that constitute the core of the urban logistics system. This model is categorized by flow into the freight station logistics area, freight station stack platform, freight train, and vehicle base logistics area (including the vehicle base platform). Firstly, the freight station logistics area marks the beginning of the retrieval transportation process. This space is dedicated to cargo unloading and sorting. Here, the cargo unloaded from the freight train undergoes swift processing and sorting in preparation for the next phase, laying the foundation for efficient cargo transportation. Secondly, the freight station stack platform serves as a transition point where cargo, once offloaded from the freight train, is moved to its next destination via a vertical transport device. It's tasked with safely transferring cargo to another location using VTSs, ensuring a consistent cargo flow. Thirdly, the freight train, primarily subways in the context of ULS, stands as the primary means of cargo transport. It ensures the cargo's efficient transportation and forms a link to the next step, playing a vital role in the cargo's safe transit. Finally, the vehicle base logistics area, inclusive of the vehicle base platform, is crucial for cargo retrieval. Here, cargo is loaded into standard roll containers and then attached to AGVs in readiness for transportation to the freight train, thereby ensuring a smooth retrieval transportation procedure. In essence, the retrieval transportation operation scenario model is instrumental in the proficient management and operation of cargo's retrieval and re-transportation within the urban logistics system. Its components are seamlessly integrated to uphold an efficient cargo transit flow, offering strategies for the smooth progression and optimization of retrieval transportation.

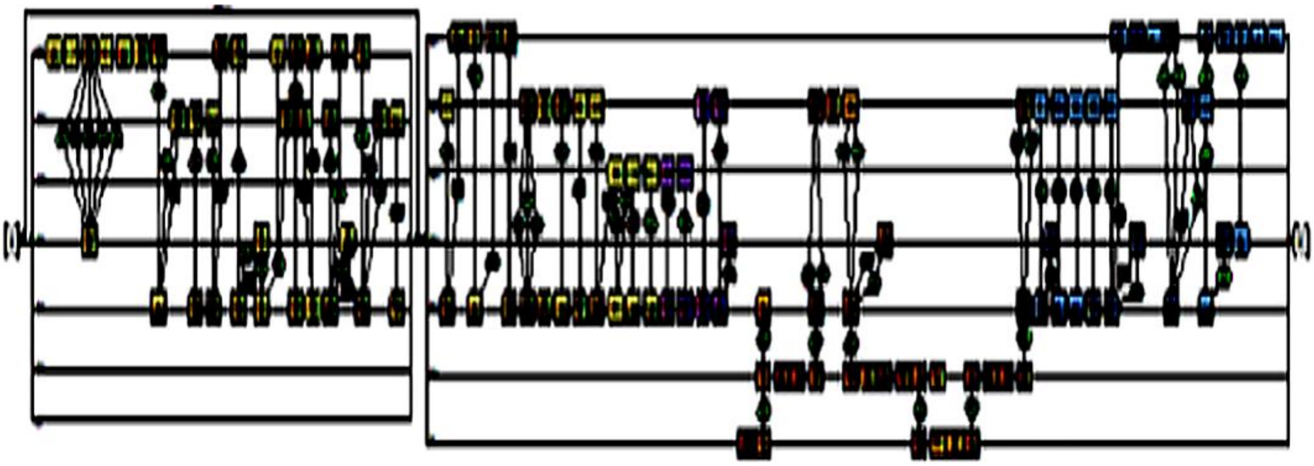

Figure 4. Retrieval logistics operation scenario model.

The retrieval transportation operation scenario model is an important model for harmoniously connecting and efficiently operating various components that constitute the core part of the urban logistics system. The retrieval transportation operation scenario model is divided into freight station logistics area, freight station stack platform, freight train, and vehicle base logistics area (including vehicle base platform) according to the flow. First, the freight station logistics area is the starting point of retrieval transportation, and it is a space where cargo unloading and sorting work are performed. Here, the cargo unloaded from the freight train is quickly processed and sorted to prepare for the next step. The foundation for efficient transportation of cargo is prepared. Second, the freight station stack platform is a place where the cargo unloaded from the freight train is transported to the next step through a vertical transport device. It is responsible for safely moving the cargo to another space using VTSs to maintain a continuous flow of cargo. Third, the freight train is the main means of transporting cargo, and it loads and transports cargo to ensure efficient transportation of cargo and connects to the next step. In ULS, this mainly refers to subways, which play a key role in ensuring safe transportation of cargo. Finally, the vehicle base logistics area (including the vehicle base platform) is an important place for the retrieval of cargo. The cargo is loaded into standard roll containers and connected to AGVs to prepare for transportation to the freight train. This ensures the smooth progress of the retrieval transportation process. As such, the retrieval transportation operation scenario model plays an important role in efficiently managing and operating the retrieval and re-transportation of cargo within the urban logistics system. Various components are harmoniously connected to maintain an efficient cargo transportation flow, and provide methods for smooth progress and optimization of retrieval transportation.

The freight station logistics area is a crucial space within the retrieval transportation operation scenario. Here, tasks crucial for the efficient retrieval and re-transportation of freight are executed. This area ensures a smooth logistics process by seamlessly connecting various tasks and links, thus guaranteeing the efficient transportation of freight. Initially, freight workers load the goods into standard roll containers, paving the way for an efficient retrieval process. The AGVs and the standard roll containers are then connected and grouped, facilitating efficient grouping and steady freight movement. Subsequently, the VTSs are used to transport the freight to the designated floor. This logistics area stands as a pivotal component of the retrieval transportation operation scenario, ensuring a harmonious and efficient flow of goods. Every step and task are interconnected, promoting the smooth progression and optimization of retrieval transportation.

The freight station dummy platform serves as the transition point where the AGVs move from the VTSs to the freight train’s boarding waiting position. This platform seamlessly integrates various stages and functions, supporting the smooth transportation and retrieval of cargo. Initially, the AGVs transition from the VTSs to the waiting position for freight train boarding. Here, cargo is primed for transportation, and preparations are made for its loading onto the freight train. Following this, cargo is elevated using the VTSs and positioned at the freight train boarding spot. At this juncture, the cargo is ready for transportation, ensuring a smooth flow into the next phase. Configured thus, the dummy platform efficiently manages cargo transportation preparation within the retrieval transportation scenario, ensuring fluid boarding and transit onto the freight train. This design contributes significantly to swift retrieval and efficient cargo transportation.

A freight train serves as a pivotal medium for the transit of cargo housed in standard roll containers. Within the freight train, a horizontal conveyor device linked to the roll container loads and transports the cargo. The train ensures safe and uninterrupted transit between the origin and destination. Upon reaching the destination, the cargo is offloaded and directed to the subsequent phase or processed accordingly.

The freight train depot logistics area, inclusive of the depot platform, is designated for the unloading of cargo from freight trains. Here, horizontal conveyors are detached from standard roll containers, allowing cargo workers to unload the goods. A streamlined workspace and system ensure the swift and secure offloading of cargo. Once offloaded, the cargo is either transported further or processed for the next operational step.

2.3.3. Simulation and verification of the integrated model

Simulation tests were conducted to validate the operational effectiveness of the integrated model, covering both the freight transport and retrieval logistics operation scenario models. These tests ensured that the system operates smoothly and without logical errors. Through simulations, the sequential order of functions and interactions between system components (such as cargo workers, AGVs, VTSs, and control systems) were checked. The simulations also tested individual scenarios and the integrated system, focusing on ensuring smooth transitions between stages, from cargo loading at the vehicle base logistics area to unloading at the freight station logistics area. Temporal analysis, along with logical analysis, provided insights into the system's execution times and identified areas where optimizations could be made, such as reducing AGV transport times or improving vertical transport with VTSs. This verification confirmed the system's design was effective and aligned with real-world constraints.

3. Results

3.1. Verification of system operation scenario

The system operation scenario is verified through model simulation. When the simulation is run, the model can be logically analyzed, and its timeline can be examined to check for any problems or errors. Logical analysis involves simulating the model to ensure that it progresses in the intended order and flow. When the simulation starts, the functions assigned to the system proceed in a specific sequence. This order may change based on the items (information) being exchanged. If the process completes successfully from beginning to end, it's considered successful. However, if an error interrupts the simulation, the model will halt. In such instances, a logical issue is present within the model. Thus, the flow or function causing the problem needs to be identified, checked, and rectified. Temporal analysis is automatically conducted during the logical analysis of the model. Typically, it represents the total time taken from the initiation to the conclusion of the model's simulation. This measurement gauges the time consumed during the simulation of actual scenarios or processes. Temporal analysis assesses the model's execution duration, aiding in its efficiency and performance evaluation. It sheds light on the model's operational speed in a real-world environment, the time required to process large datasets, among other factors. Hence, temporal analysis offers significant insights into the model's applicability in real-world scenarios. Generally, default random values are used to represent the total time, which might not align with real-time values. By accurately reflecting time within the model, one can discern the duration each model segment requires and pinpoint where the majority of time is expended. Time inputs are incorporated into the duration attribute of each function, and temporal analysis is conducted using these input values during model simulation. For simulating the integrated model, it's crucial to designate time to the duration attribute of each function. Basic rules have been established to assign time to the duration attribute of every function present in the integrated model. The allocated values are detailed in **Table 2** below.

Table 2. Allocation of function execution time.

Category	**Set value**
Signal transmission & reception	0.5 second
Data generation function in the system	0.5 second
Physical verification of the person	random (varies depending on distance, weight, floor conditions, etc.)
Physical movement within the system	random (varies depending on distance, weight, floor conditions, etc.)
Allocate appropriate time after confirming the contents for items not covered by basic regulations	

3.2. Verification through simulation

This study conducted simulations on the integrated model combining both the cargo transportation operation scenario and the retrieval transportation operation scenario. Through these simulations, we confirmed the absence of logical discrepancies. This study aimed to construct and validate an integrated model for both scenarios using simulation techniques. By doing so, we ensured there were no logical issues, establishing that the simulation of the integrated model is crucial for assessing the interaction between the two scenarios and the overarching system operation. Verifying the model's logical consistency and precision through simulations was pivotal in underpinning the study's reliability. In essence, by ascertaining that the integrated model for both cargo transportation and retrieval transportation operation scenarios interacted effectively and guaranteed fluid operation, we demonstrated the attainment of our research objectives and the credibility of our findings.

Throughout the model integration phase, this study consistently rectified any logical inconsistencies and challenges that arose within the model. We also undertook a logical analysis of the integrated model via simulation to corroborate its relevance for the urban logistics system operation scenario. Furthermore, we carried out a temporal analysis (i.e., a timeline analysis) to determine the ultimate execution time.

The findings from the model's verification and simulation provide several managerial actions and policy recommendations that can optimize decision-making in urban logistics and infrastructure planning. First, the model's successful simulation of both cargo transportation and retrieval transportation scenarios highlights the importance of thorough system analysis before implementation. Managers can use this approach to identify potential issues and inefficiencies in logistics systems before they become operational, ensuring smoother execution and reducing costly errors. The temporal analysis, which assesses the time taken to execute various system functions, offers valuable insights into where delays or bottlenecks might occur. Urban logistics planners can apply these insights to prioritize the improvement of processes that consume excessive time, enhancing the overall efficiency of the system. Specifically, time allocations for different system functions should be regularly reviewed and optimized to ensure that urban logistics operations remain swift and cost-effective. Furthermore, the simulation's ability to detect logical discrepancies suggests that continuous monitoring and validation should be integrated into decision-making processes. This proactive approach will help identify and correct problems early, avoiding disruptions in the logistics flow. Policymakers should also consider investing in technologies that support real-time data integration and simulation tools, which can be instrumental in testing new infrastructure and logistics models. By integrating these strategies into urban logistics and infrastructure planning, cities can optimize the flow of goods, reduce congestion, and enhance the resilience of logistics systems.

4. Discussion

Modern cities grapple with the dual challenges of managing logistics and goods movement efficiently, while also mitigating traffic congestion and environmental concerns. With a mounting recognition of the imperative to devise innovative urban logistics systems that leverage underground spaces sustainably, this study underscores the value of such systems. Hu et al. (2023) evaluated the metro-based underground logistics system for collaborative passenger and freight transport in megacities, emphasizing their zero-carbon, congestion-free, and high-capacity features. They introduced an equilibrium chance-constrained programming approach to address the M-ULS network planning problem considering uncertain demand and costs. Their study used a two-tier M-ULS network based on a satellite city development project, optimizing decisions related to location, allocation, capacity, inventory, pipeline layout, and flow routing, focusing on Beijing, China, which is distinct from the subway systems in Korea. Xu et al. (2022) also suggest that the M-ULS can be a revolutionary solution during city-level disasters because of its operational efficiency. This system could enhance the performance of city logistics during unprecedented situations like the COVID-19 outbreak. In addition, Roodt et al. (2020) explored the extensive replacement of Sydney’s heavy-rail signaling and control systems. Emphasizing the anticipated years-long duration and wide-ranging impacts, they showcased the early adoption of Systems Engineering to navigate the intricacies and risks. Specifically, their research delves into the real-world use of Model-Based Systems Engineering (MBSE) during the conceptual phase of New South Wales’ Digital Systems Program. It highlights MBSE’s role in understanding operational and maintenance aspects, establishing architecture, and guiding requirements. However, since their research is focused on Sydney’s heavy-rail signaling and control systems, it may be challenging to directly apply it to the ULS utilizing the metropolitan subway network in South Korea. Thus, this study introduces an integrated model for the ULS in South Korea’s metropolitan regions, addressing the challenges of urban logistics and freight transportation. We developed both a detailed and integrated model based on urban logistics operation scenarios, then tested and validated these through simulation. A key focus of this study was the innovative concept of underground logistics. To validate ULS operations, we explored various operational scenarios using conceptual modeling, system structure analysis, and simulation techniques. The operational scenario distinctly differentiated between the integrated and detailed scenarios, categorizing spaces based on scenario flow for clarity. This study shows that bolstering logistics and freight transportation efficiency through underground utilization can ameliorate urban traffic and environmental woes. The ULS operational scenario modeling, set against the backdrop of the Seoul Metropolitan Area, holds the promise of offering lucid operational directives, elevating the system’s efficiency and dependability. During the detailed model’s creation, we harmonized terms between the freight transportation and retrieval transportation scenario models for consistency. The integrated model also mirrored any modifications from the detailed model to ensure coherence. Di et al. (2022) examined a subway-based underground logistics system in Beijing, considering both passengers and freight. Our study, however, excluded passenger considerations, warranting further analysis in this area. Ozturk and Patrick (2018) also propose an innovative freight transport method using urban rail transit systems. This method, gaining popularity in certain regions, enables shared railway use between passenger and cargo trains within city confines. Their study introduces a decision support framework alongside mathematical methods for optimal goods distribution in this context. With predetermined demand and unique client delivery times, the focus lies on a single rail line with selective stations serving as goods loading and unloading platforms. Their initial discussions on a two-station scenario lead to an extended multi-station context, wherein various algorithms and models are introduced, which supports partially our findings.

As a consequence, this study highlights the potential of underground logistics systems (ULS) in addressing these challenges, drawing from the findings of Hu et al. (2023), Roodt et al. (2020) and Xu et al. (2022). The integration of underground spaces into urban logistics can reduce carbon emissions, alleviate congestion, and increase system capacity. By adopting an equilibrium chance-constrained programming approach, Hu et al. (2023) optimized ULS network planning, which can serve as a model for decision-making in urban logistics infrastructure. The emphasis on system integration and spatial planning is crucial for optimizing both location and capacity, which directly influences cost-effectiveness and operational efficiency. From a managerial perspective, several actionable insights emerge. First, cost-benefit analyses should factor in both direct and indirect costs of ULS implementation, including construction, maintenance, and operational efficiency gains. Strategic planning should prioritize underground logistics’ ability to mitigate traffic congestion, reduce environmental impact, and improve system resilience during emergencies, as evidenced during the COVID-19 pandemic (Xu et al., 2022). Managers can leverage this study’s findings to guide long-term infrastructure investments, particularly by focusing on the integration of rail transit and freight systems. Furthermore, the adoption of simulation-based decision support tools, like those used in this study, enables more accurate forecasting of operational performance and the identification of inefficiencies before implementation. As cities transition to sustainable urban logistics models, these insights will be essential for informed decision-making and ensuring a competitive, sustainable urban infrastructure. While this study successfully constructed and validated detailed and integrated models, it has limitations. The ULS’s downsides, such as the high initial and maintenance costs and augmented security risks due to additional entrances, were not thoroughly examined. In addition, the dataset has limitations, including geographic constraints, potential biases due to untracked operations, and data gaps during peak periods or special events. Furthermore, while the detailed operation scenario simplified the model-building process, inconsistencies in terminology and subject behaviors persisted. Addressing these will require stringent term management and standardization, along with refining repetitive sections. These gaps present avenues for subsequent research. It’s paramount to consistently collate feedback from ULS implementations and engage with a broad spectrum of stakeholders to craft a holistic system. This research, nonetheless, stakes a claim in the ongoing discourse on refining urban logistics systems, poised to influence urban development positively and amplify national competitiveness via the inception of sustainable, avant-garde urban logistics systems.

5. Conclusions

This study explores the development and implementation of an innovative ULS leveraging underground spaces in South Korea's metropolitan regions. By addressing the challenges of urban logistics and freight transportation, the study proposes detailed and integrated models based on urban logistics operation scenarios, which were tested and validated through simulation techniques. The primary focus was on the concept of underground logistics, with various operational scenarios explored using conceptual modeling and system structure analysis. The findings suggest that enhancing logistics and freight transportation efficiency through underground utilization can significantly alleviate urban traffic congestion and environmental issues. The ULS operational scenario modeling, specifically tailored for the Seoul Metropolitan Area, provides clear operational directives aimed at improving system efficiency and reliability. The implications of this study are as follows. The innovative use of underground spaces for logistics can transform urban transportation, reduce surface traffic, and minimize environmental impacts. This approach can enhance urban development and national competitiveness by creating sustainable, advanced logistics systems. This study highlighted the transformative potential of utilizing underground spaces for logistics, emphasizing their role in optimizing urban transportation, alleviating surface congestion, and reducing environmental impacts. By fostering sustainable and advanced logistics systems, this approach could contribute to urban development and enhanced national competitiveness.

However, this study has several limitations. It did not thoroughly examine the high initial and maintenance costs associated with the ULS, nor did it address augmented security risks due to additional entrances. Additionally, while the detailed operation scenario simplified the model-building process, inconsistencies in terminology and subject behaviors persisted, necessitating stringent term management and standardization. These gaps present opportunities for further research. To overcome these limitations, it is crucial to consistently collect feedback from ULS implementations and engage with a broad spectrum of stakeholders to refine the system. Future research should focus on addressing cost concerns, enhancing security measures, and standardizing terminology to ensure the ULS's practical viability and long-term success.

Author contributions: Conceptualization, UC and JUK; methodology, GL; software, UC; validation, UC, GL and JUK; formal analysis, UC; investigation, GL; resources, UC; data curation, GK; writing—original draft preparation, UC and GL ; writing—review and editing, AK and JUK; visualization, UC; supervision, AK and JUK; project administration, JUK; funding acquisition, UC and JUK. All authors have read and agreed to the published version of the manuscript.

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