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Optimizing Prefabricated Supply-Schedule Synchronization for Cold-Region Residential Retrofits

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Abstract:

This paper investigates the coordinated optimization of prefabricated component supply and on-site construction scheduling for the retrofit of aging residential compounds in severe cold regions. The study frames the retrofit workflow as a coupled supply–schedule system subject to winter constraints such as frozen ground, prolonged curing time of concrete, limited laydown areas, and intermittent logistics caused by snow and ice. Building on supply chain management principles, critical path scheduling, and digital site control, the paper proposes a just-in-time, batch-release supply policy synchronized with an adaptive construction sequence. The approach integrates weather-aware planning rules, buffer design for transport disruptions, and an intelligent dispatch mechanism that updates priorities using real-time signals from equipment, inventory, and meteorological feeds. The proposed framework aims to reduce idle inventory on site, prevent process clashes among lifting, casting, and fit-out tasks, and preserve quality under low-temperature conditions. Expected benefits include shorter effective project duration, lower handling and heating costs, improved utilization of cranes and crews, and enhanced robustness against weather volatility. The paper concludes with implementation guidelines, policy implications for cold-region urban regeneration, and a road map for validating the method with digital twins and field pilots in multiple cities. These validation efforts are crucial for bridging the gap between theoretical models and practical implementation in this understudied context.

Keywords: Cold Climate Construction; Prefabricated Construction; Supply Chain Integration; Dynamic Scheduling; Resource Optimization

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1. Introduction

1.1 The Winter Retrofit Challenge: Climate and Site Constraints

In many cities located in high-latitude and high-altitude belts, legacy residential compounds built several decades ago now face structural aging, energy inefficiency, and functional obsolescence. Winter retrofit campaigns in such areas are challenged by persistent sub-zero temperatures, frozen soil layers that complicate excavation and foundations, and significant constraints on concrete curing and enclosure works. Beyond the direct climatic effects, the retrofit context typically involves confined courtyards, narrow internal roadways, and occupied premises, all of which limit storage and maneuvering space for heavy components and mobile cranes. As a result, even when prefabrication is adopted to shorten on-site exposure, poor alignment between the arrival of components and the readiness of installing work faces can lead to queueing, re-handling, and congestion on site.

Prefabricated construction promises to externalize value-adding operations to controlled factory environments, improving quality assurance while compressing on-site duration. However, its performance depends on the tight synchronization of upstream fabrication, midstream transportation, and downstream erection. In the winter, the retrofit of occupied compounds, as-built deviations, intermittent road accessibility due to snow or ice, and the need to stage installations around residents' access windows further intensify coordination demands. When components arrive too early, they occupy scarce laydown areas, interfere with traffic management, and incur additional protection or heating costs. When parts arrive late, cranes and workers must wait, heating and temporary setups need to run longer, and key jobs may be forced into colder times. Different trades often get in each other's way: lifting parts, pouring or grouting with heat, and later sealing or insulating can all fight for the same space and tools if the plan is not very strict. So, to really get the benefits of prefabrication, planning must change from step-by-step work to tightly coordinated work.

To handle these linked problems, it helps to use a systems view where supply and schedule are treated as one decision. Instead of sending prefabricated parts as soon as the factory is ready, a "pull" system can be used. In this way, batches are sent only when site progress, work-area readiness, and short-term weather allow it. This reduces the need for extra stock and lets the schedule adapt with built-in slack, weather-aware shifts, and fast re-ordering of tasks. To make this work, digital tools are key: sensors to track shipments and parts, short-term schedules, and auto dispatch rules can turn real-time updates into clear work plans. In very cold regions, extra winter methods are also needed—like heated covers, fast-setting binders, and backup transport routes—so that efficiency does not reduce safety or quality.

1.2 Literature Review: Supply Chain Synchronization and Resilience

In the last ten years, research on prefabricated construction supply chain management has grown quickly. Many studies have focused on efficiency, resilience, and digital tools. Han, Yan, and Piroozfar gave a full review of supply chain management for prefabricated construction and showed that good coordination between suppliers, transporters, and site managers is key to cutting waste and delays [1]. They also pointed out that in very cold climates, poor coordination becomes a bigger problem because transport and site work are more fragile than in normal weather.

Zhang and his team studied how to improve the delivery of prefabricated parts using a just-in-time (JIT) approach. They built models with two goals: reducing both delivery costs and waiting times [2]. Their results showed that planned arrivals and limited buffering helped projects stay on schedule, which is especially useful in retrofit projects where storage space is small. Yang and co-authors took this further by creating data-driven systems for logistics cooperation. Their method lets suppliers and contractors re-plan deliveries together when disruptions happen in real time [3]. They showed that sharing information through digital systems can reduce the bullwhip effect and make deliveries more reliable.

Nesarnobari gave another view, which was a broad review of off-site construction supply chain management. The study said resilience and flexibility are most important in uncertain settings [4]. It also noted that while lean JIT systems save on storage costs, mixed strategies with small buffers can protect projects from climate shocks. Liu, Ma, and Fu studied resilience too, and found that digital tools like IoT sensors and predictive analytics are very important for making supply chains more adaptable [5]. Together, these studies converge on the insight that prefabricated construction success in adverse contexts relies not only on optimized schedules but also on collaborative and technology-enabled supply networks.

In sum, the literature underscores the interplay between logistics optimization, resilience design, and intelligent coordination. Yet, a clear research gap remains regarding how these principles can be operationalized specifically in severe cold retrofits of aging residential compounds, where seasonal weather constraints and resident occupancy impose unique limitations. This paper aims to bridge that gap by integrating supply chain optimization with adaptive scheduling models tailored for winter conditions. While the existing body of research provides valuable theoretical foundations and general methodologies, a significant gap remains in its application. There is a lack of a comprehensive and operational framework that specifically addresses the co-optimization of supply chain logistics and construction scheduling under the unique compounded constraints of severe cold climates, occupied residential retrofits, and spatially confined sites. This study seeks to bridge this gap by developing and proposing such an integrated framework.

1.3 Research Aim and Framework

The research framework of this paper is structured to address the identified gap progressively. To address the aforementioned problems, this research is structured in four progressive steps:

First, the study analyzes the impact of severe cold climates on construction operations, focusing on frozen soil, delayed concrete curing, logistics difficulties, and site storage limitations. This diagnosis forms the empirical baseline.

Second, the paper investigates the coordination problems between prefabricated component supply and construction scheduling, detailing cases of premature arrivals, late deliveries, and multi-trade conflicts. This step clarifies the operational pain points that obstruct efficient retrofitting in winter.

Third, based on supply chain theory and scheduling optimization methods, the paper proposes collaborative optimization strategies. These include just-in-time batch supply, critical path–based scheduling adjustments, and digital dispatch systems incorporating IT and artificial intelligence. By embedding climate-responsive methods such as accelerated concreting and heated enclosures, the proposed framework aligns supply and schedule within the constraints of severe cold.

Finally, the paper develops implementation guidelines and policy suggestions, linking theoretical findings to practical pathways for government, industry, and contractors. The framework thus follows a logical progression: (1) Problem identification; (2) Diagnosis of climate and supply–schedule impacts; (3) Optimization design; (4) Implementation and significance.

This structure ensures that both the theoretical and applied dimensions of the study are addressed, with clear relevance to urban renewal in cold regions.

2. Constraints and Challenges Imposed by Severe Cold Climate

Severe cold makes all existing problems worse. Frozen soil slows foundation work, low temperatures weaken concrete, bad roads disrupt transport, and limited storage space causes congestion. If not well planned, these problems add up, leading to delays, higher costs, and risks to quality. This shows why supply–schedule integration strategies designed for extreme weather are necessary.

2.1 Frozen Ground and Foundation Works

During winter months, soil layers in northern and high-altitude regions are often frozen to considerable depths. This condition severely complicates excavation, piling, and foundation construction. Frozen soil requires additional removal, thawing, or replacement, leading to extended durations and added costs. In retrofit projects where buildings must remain partially occupied, the risks of ground movement or uneven thawing also heighten safety concerns for both workers and residents. The treatment of frozen ground often demands heating, chemical agents, or protective enclosures, all of which increase the complexity of site operations [6].

2.2 Low Temperature Effects on Concrete Works

Concrete work is very sensitive to freezing weather. When the air temperature drops below zero, the hydration process slows down a lot. This means concrete gains strength more slowly and cracks more easily. If this is not managed well, long-term durability problems may appear. To reduce these risks, builders use methods like pre-heating aggregates, adding antifreeze chemicals, or covering the work area with heated shelters. These solutions, however, bring higher costs and more energy use, which also raises concerns about sustainability and carbon emissions [7].

2.3 Winter Transportation Challenges

Roads in cold regions become difficult to use because of snow, ice, and poor visibility. This increases the chance of delays and also the risk of damaging parts during transport. Prefabricated elements are large and sometimes fragile, so they need extra care in these conditions. Loading and unloading parts is also more dangerous and slower when snow or ice is present, making crane work less efficient. Such transport delays often lead to schedule problems and waiting time on site [8]. These disruptions also make it harder to keep concrete curing and foundation work on track, since both require a steady supply and continuous work.

2.4 Restricted Laydown Areas and Site Storage

Retrofit projects in old housing areas often have very limited space. Small courtyards and narrow roads reduce the area available for storing prefabricated parts. Winter weather makes this worse: snow and ice take up usable space, forcing workers to move components many times or crowd equipment into tight areas. Both situations reduce safety and productivity. Poor storage planning can

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also block resident access, cause equipment traffic jams, and slow down sequential work. In winter, lack of storage space makes both early deliveries (which add to congestion) and transport delays (which leave work areas waiting for parts) even more harmful [9].

3. Problems in Prefabricated Component Supply and Construction Scheduling

Retrofitting old housing in very cold regions creates challenges in logistics, sequencing, and resource use. Even with prefabrication, poor coordination between supply and construction often reduces project performance. These issues come from a deeper problem: the gap between supply chain logistics and on-site scheduling, which becomes worse under cold climates and tight site conditions. Three common problems can be seen: early arrival of parts, late arrival of parts, and conflicts between different tasks.

3.1 Premature Arrival of Prefabricated Components

One of the most common issues is parts arriving too early. Although just-in-time (JIT) logistics aim to reduce inventory, suppliers sometimes send parts ahead of time to avoid delays or ease pressure in the factory. This causes congestion on site, especially in small housing compounds with limited space. Snow and ice reduce storage space further, forcing workers to pile up parts in the wrong places or move them many times to clear work zones.

Early arrivals also increase heating and protection costs. In freezing weather, components must often be insulated or heated to avoid damage. This is especially important for items like precast concrete panels and insulated façade modules. Excessive on-site storage not only escalates costs but also poses risks of component damage from snow load, ice formation, or accidental impacts in congested courtyards [10]. This issue of premature arrival is critically magnified by the restricted laydown areas, turning a mere logistical inefficiency into a major safety and operational bottleneck.

Furthermore, site safety may be compromised as residents in occupied compounds are forced to navigate around large stored components, heightening the risk of accidents. These negative effects collectively diminish the efficiency advantage originally expected from prefabrication.

3.2 Delayed Arrival of Prefabricated Components

The second major problem is the late delivery of prefabricated elements, which can stall critical construction sequences. In severe cold regions, road conditions frequently deteriorate due to snow, ice, and storms, disrupting transport schedules and preventing timely delivery. Unlike conventional materials that can often be substituted or sourced locally, prefabricated components are custom-made and integral to the structural and envelope system. As a result, any delivery delay directly halts progress. Delays are especially problematic when they affect the critical path of the project. For example, if wall panels or floor slabs arrive late, crane crews and assembly teams have to wait. This wastes resources and raises labor costs [2]. In addition, heating for concrete and temporary enclosures must run longer, using more energy. Late deliveries also cause chain reactions: follow-up work like insulation, mechanical and electrical systems, and finishing cannot start until the main modules are in place. Because these tasks depend on one another, even small delivery delays can have a big impact. The combined effect of late deliveries and longer heating needs creates a feedback loop that raises both energy costs and project time.

Research on logistics optimization shows that using predictive analytics and weather forecasts in delivery planning can lower these risks [3]. However, many retrofit projects do not have real-time coordination systems. Contractors often rely on fixed schedules that cannot adapt to changing winter conditions. Without flexible systems, supply readiness and site needs are often out of sync.

3.3 Multi-Process Conflicts and Resource Clashes

The timing problems caused by early or late deliveries often lead to other issues, especially conflicts between tasks and competition for resources. In winter retrofit projects, key activities like crane lifting, heated grouting, and waterproofing usually need to follow one another closely. If the schedule is not well coordinated, equipment, workers, and workspaces overlap, creating inefficiency and safety risks. For example, a crane may be needed both for lifting heavy panels and for setting up heating equipment. If this happens, tasks must be done one after another instead of at the same time.

This problem is worse in retrofit projects where people still live in the buildings. Contractors must plan work to reduce disturbance, limit working hours, and fit tasks into shorter time windows. Inadequate planning can lead to bottlenecks where crews wait for preceding tasks to be completed, elongating the overall project duration. These conflicts represent the ultimate manifestation of failed synchronization, where the combined pressures of climatic adversity (e.g., limited work windows due to cold, the need for heated enclosures) and site constraints (e.g., lack of space) converge to defeat the planned workflow. These inefficiencies not only increase costs but also heighten risks of accidents in slippery, cold environments [4].

Existing research has emphasized the importance of collaborative planning platforms and integrated scheduling systems in managing such multi-trade conflicts. Digital twins and IoT-enabled site monitoring, for instance, can allow managers to simulate sequences, identify resource clashes, and dynamically re-allocate crews [5]. However, adoption of many cold-region retrofits remains limited due to cost, training barriers, and fragmented project governance. Consequently, resource conflicts remain a persistent barrier to achieving the promised efficiency of prefabricated methods.

3.4 Summary of Problems

In summary, premature arrivals congest sites and raise storage costs, delayed arrivals stall critical activities and extend heating needs, and multi-process conflicts produce inefficiencies and safety risks. Each of these problems is magnified by the severe cold context, where frozen soil, sub-zero temperatures, and snow-laden roads constrain flexibility. Together, these challenges demonstrate that prefabricated construction in cold-region retrofits requires not only technical adaptations but also a systemic rethinking of how supply and scheduling are jointly optimized. Without such integration, the benefits of prefabrication risk being offset by climate-induced inefficiencies.

4. A Framework for Coordinated Optimization: Strategies and Enablers

In direct response to the coordination failures detailed in Chapter 3—namely, premature and delayed component arrivals, and multi-process conflicts—this section proposes a multifaceted framework for coordinated optimization. The recommendations are designed to counteract the root causes of these problems, which are exacerbated by the severe cold constraints analyzed in Chapter 2. The strategies are categorized into: (1) operational tactics for supply chain and scheduling integration (Section 4.1), and (2) collaborative and institutional enablers to ensure effective implementation (Section 4.2).

4.1 Operational Optimization Strategies

4.1.1 Just-in-time and batch-based supply

To directly address the problem of premature arrivals and the associated storage congestion (Section 3.1), a just-in-time strategy should be adopted where prefabricated components are delivered in smaller batches aligned with on-site installation needs. By subdividing shipments into daily or weekly lots, contractors can minimize on-site inventory while ensuring that crews always have the components they need for the next work package. This approach requires close integration of supplier production plans with site demand forecasts [1].

4.1.2 Integration of critical path scheduling with supply logistics

Mitigating the risks of delayed arrivals halting critical activities (Section 3.2) requires explicitly linking construction schedules with delivery timetables through digital platforms.

The critical path method (CPM) can help find tasks where on-time deliveries are most important. Logistics planning should focus on these key components. If deliveries are matched with the critical path, the chance of delays stopping project progress is reduced [2]. In addition, float activities can be used to handle supply changes without harming the overall schedule.

4.1.3 Intelligent dispatch and monitoring systems

To deal with timing problems caused by both early and late arrivals (Sections 3.1, 3.2), smart dispatch systems can be set up to adjust delivery and installation plans in real time. By using IoT sensors on trucks, GPS tracking, and weather data, managers can see possible transport problems and change schedules quickly [3]. Machine learning can improve predictions of road and traffic conditions, helping managers make proactive choices. This lowers the risk of both early and late arrivals and makes the system stronger.

4.1.4 Climate-responsive construction practices

Besides logistics, keeping good structural quality in cold weather is critical (Section 2.2). Construction methods should be adjusted for low-temperature conditions. Examples include using fast-setting binders, antifreeze chemicals, and heated enclosures to allow concreting even below zero [4]. Prefabricated parts can also be pre-heated during transport and installed right away to prevent freezing damage. Pre-heating parts during delivery helps protect material strength and allows work to continue without delay, even in freezing conditions. These steps ensure that supply and schedule integration does not reduce quality or durability.

4.2 Collaborative and Institutional Enablers

4.2.1 Comprehensive construction planning

Project managers should prepare detailed winter construction plans early. These should include climate forecasts, buffer times for weather delays, and backup transport routes. Planning alternate routes ahead of time is especially important against winter transport risks like snow and ice (Section 2.3). Layout plans should also reserve space for temporary storage, heating stations, and safe paths for residents. Such careful preparation reduces the chain effects of unexpected delays [5].

4.2.2 Multi-stakeholder collaboration

Good coordination needs active teamwork between con-

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tractors, suppliers, designers, and supervisors. Shared platforms should be used to give real-time updates on deliveries, production, and site readiness. This avoids delays in communication that can cause early or late arrivals. Joint planning workshops and shared project offices can further improve communication.

4.2.3 Promotion of intelligent scheduling systems

Governments and industry groups should promote digital construction management systems. Smart scheduling platforms that use big data and AI can adjust resources automatically when disruptions happen. For example, if a truck is delayed, the system can suggest re-ordering non-critical work to keep progress steady. Pilot projects in cold regions show that these systems cut idle time and improve safety [6].

4.2.4 Policy and technical standard development

Finally, supportive policies are needed to make these practices standard. Governments should set rules for winter construction in cold regions, such as supply chain coordination, heating methods, and digital technology use. Incentives like subsidies for digital twins or tax benefits for energy-efficient winter construction can help the industry adapt faster. Clear technical standards also provide a guide for training workers, making sure that advanced scheduling and logistics methods are used correctly.

4.3 Summary of Recommendations

The suggested measures converge on three priorities: Optimization of supply–schedule coupling through JIT and critical path integration; Deployment of intelligent systems for real-time dispatch, monitoring, and adaptive scheduling; Institutional support via comprehensive planning, multi-stakeholder collaboration, and supportive policy frameworks.

Collectively, these strategies not only mitigate the identified problems of premature arrivals, delayed deliveries, and process conflicts but also enhance the long-term resilience and sustainability of retrofits in severe cold regions.

5. Conclusion

5.1 Key Findings

This paper has examined the coordinated optimization of prefabricated component supply and construction scheduling in the retrofit of aging residential compounds in severe cold regions. The analysis first identified four major climate-induced constraints: frozen soil, low-temperature effects on concrete curing, winter transportation challenges, and restricted laydown areas. It then discussed three core problems in supply–schedule coordination: premature component arrivals causing storage congestion, delayed arrivals halting critical activities, and multi-process conflicts leading to resource clashes.

In response, a series of recommendations was proposed. On the supply side, just-in-time and batch-based delivery mechanisms were emphasized to prevent both premature and delayed arrivals. On the scheduling side, integration of critical path methods with supply logistics and the adoption of intelligent dispatch systems were identified as critical enablers. Climate-responsive construction techniques such as antifreeze admixtures and heated enclosures were suggested to safeguard quality under extreme conditions. Furthermore, comprehensive winter-specific planning, multi-stakeholder collaboration, and supportive policies were recommended to institutionalize best practices. Collectively, these strategies form a holistic framework for improving efficiency, reducing costs, and ensuring safety in cold-region retrofits.

5.2 Research Significance

This study addresses a critical challenge in urban renewal: how to efficiently and safely retrofit aging residential buildings in severe cold climates using prefabricated construction. The findings of this paper carry practical, social, and industry-wide implications. From a practical perspective, the proposed optimization strategies enable contractors to minimize idle resources, reduce re-handling, and maintain productivity despite weather volatility. For industry stakeholders, the adoption of intelligent scheduling systems fosters digital transformation and resilience within construction supply chains. By integrating supply chain optimization with adaptive scheduling models tailored for winter conditions, this research directly addresses the gap identified in the literature regarding the operationalization of general principles in the specific context of severe cold, occupied retrofits. Socially, successful retrofits in severe cold regions directly improve the living standards of residents in aging compounds, ensuring warmer, safer, and more sustainable housing. Moreover, the integration of prefabricated construction under extreme climate conditions provides a reference model for future green and digital transitions in the construction sector worldwide.

5.3 Limitations and Future Study

This paper primarily relied on secondary data from existing literature, case studies, and theoretical models. While the findings highlight key challenges and solutions, they are limited by the absence of primary empirical data such as site surveys, interviews, or real-time pilot experiments. Future research should therefore focus on collecting first-hand data from active retrofit projects in severe cold regions to validate the proposed framework. Surveys of contractors, suppliers, and residents could provide more granular insights into coordination bottlenecks. In addition, field trials of intelligent dispatch systems and digital twin models would strengthen the practical applicability of the recommendations. Future studies could also explore cross-regional comparisons, examining how strategies differ between various climate zones. Such investigations would further enrich the knowledge base and support broader scalability of optimized prefabricated construction practices.

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