Optimization of Temporary Modular Unit Logistics with Circular Flow

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Abstract – Temporary modular construction units are designed for repeated installation, dismantling, and redeployment across multiple sites, thereby reducing material waste and embodied emissions compared to single-use building solutions. This reuse creates a circular flow of modules, in which units return from completed projects and are redeployed to new sites. Managing these circular flows creates logistical challenges: returned units arrive with varying quality (some in good condition and immediately reusable, while others require refurbishment), and both pickup and delivery must respect time-window constraints. A central depot provides buffering for reusable and repairable units, while a factory performs refurbishment and new production under capacity constraints. Demand that is not satisfied within its delivery window is treated as unmet demand and penalized accordingly. We develop a discrete-time, time-expanded optimization model to jointly plan pickup timing, routing, depot buffering, refurbishment, and new production in centralized modular construction logistics. Through numerical experiments, we investigate how demand intensity, supply variability, production capacity, holding and service costs, and time window lengths affect routing patterns, inventory levels, service delays, and unmet demand. The results highlight the operational value of lead-time flexibility in circular modular construction supply chains.

Keywords –
Modular construction; Circular economy; Reverse logistics; Optimization; Multi-echelon logistics

1. Introduction

Modular buildings are widely used as temporary facilities in construction, infrastructure, and industrial projects where flexibility and fast deployment are required. Instead of investing in permanent structures for each project, companies deploy standardized units that can be installed, dismantled, and redeployed across multiple sites. This approach enables the repeated reuse of assets and can significantly reduce material waste, embodied emissions, and investment costs over the lifetime of the units. As such, modular construction is a key enabler for the Circular Economy in construction.

Once a temporary construction project comes to an end, modular units are dismantled and become available for reuse in the logistics network. Depending on their physical condition upon return, units may either be reused *as-is* with minimal on-site retouching or require refurbishment at a factory before redeployment. Furthermore, returned units may not be redeployed immediately if no matching client exists and may therefore require temporary storage. Managing these return flows together with forward deliveries creates operational challenges, particularly when storage capacity, production capacity, and delivery times are limited.

Throughout this paper, the term *returns* (or supply) refers exclusively to modular units returning from completed projects, while newly produced units originate only from the factory. From a logistics planning perspective, modular construction systems differ from traditional closed-loop supply chains in several important respects. First, returned units must be collected within pickup time windows determined by dismantling schedules at construction sites rather than at fixed return times. Second, demand is associated with delivery time windows, where late delivery leads to service penalties or unmet demand. Third, the refurbishment of returned units and the production of new units compete for limited factory capacity. These features create strong interdependencies between routing, inventory, refurbishment, and production decisions across multiple echelons of the supply chain.

Previous research has highlighted the sustainability advantages of modular and prefabricated construction, primarily through waste reduction and improved lifecycle performance. Jaillon and Poon [1] and Kamali and Hewage [2] focus on environmental benefits relative to conventional construction, while Tingley et al. [3] emphasize design-for-deconstruction strategies that enable reuse and refurbishment. Chen et al. [4] indicate the relevance of optimized logistics to enable more sustainable construction. Operational planning aspects specifically of modular construction logistics have received limited attention. Hsu et al. [5] propose a two-stage stochastic programming model integrating manufacturing, transportation, and inventory decisions under demand uncertainty, but their focus is restricted to forward flows and does not explicitly model return processes or repeated reuse cycles. More broadly, the closed-loop supply chain literature highlights the importance of reverse flows for inventory dynamics [6], while routing studies with time windows emphasize the operational impact of time-constrained logistics decisions [7]. However, these research streams have not yet been integrated in the context of modular construction logistics. Ding et al. [8] highlight the lack of integrated frameworks that simultaneously address both forward and reverse flow in construction.

Despite this growing literature, limited attention has been paid to the integrated operational planning problem that arises when modular units circulate repeatedly between clients, depots, and factories under time and capacity constraints. In particular, existing models do not simultaneously capture quality-dependent return flows, pickup and delivery time windows, refurbishment versus new production capacity trade-offs, and multi-echelon inventory interactions specific to modular construction systems. This gap is also evident in practice. Modular construction providers frequently face timing mismatches in which returned units become available before demand materializes, or demand arises before sufficient reusable units are ready. Planners must then balance direct shipment, temporary storage, refurbishment, and new production decisions. In practice, such decisions are often made heuristically based on experts' opinions, without integrated optimization support that accounts for the interdependencies between return quality, timing constraints, and capacity allocation across the network.

To address this gap, in this paper, we develop a discrete-time planning model for a centralized modular construction logistics network with circular flows. Specifically, we propose a unified multi-echelon optimization model that explicitly captures the circular flows of modular units between projects, a central depot, a factory, and clients. The objective of the model is to minimize total system costs by jointly optimizing pickup timing, routing decisions, depot inventory levels, refurbishment activities, and new production, subject to pickup and delivery time windows and factory capacity constraints. We explicitly distinguish between two quality classes of returned units-immediately reusable and repairable-and model their different routing and processing options. Repairable units may undergo refurbishment at the factory, while reusable units can be redeployed directly or buffered at the depot.

Through an extensive numerical study, we provide managerial insights into how demand variability, return variability, production and refurbishment capacity, holding and service cost levels, and pickup and delivery lead-time flexibility affect system performance.

The remainder of the paper is organized as follows. Section 2 introduces the problem description and the notation used. Section 3 presents the mathematical formulation of the proposed optimization model. Section 4 describes the design of the numerical experiments and discusses the results. Finally, Section 5 concludes the paper and outlines directions for future research.

2. Problem Description

The logistics network operates as a multi-echelon system with four node types, each serving a distinct role in the circular flow of modular units: Supply, Depot, Factory, and Client, as shown in Figure 1. We consider

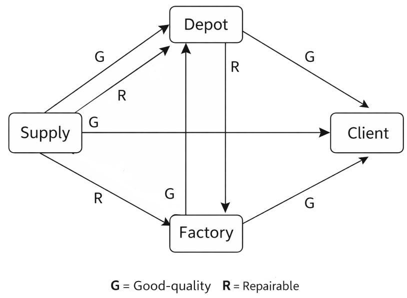

Figure 1: Modular construction logistics with circular flows.

a discrete-time, single-product, full-information setting where all future supply returns, their quality composition, and all client orders (including their lead-time windows) are known at the start of the planning horizon. We incorporate lead-time windows for both supply pickup and demand delivery. These windows specify the allowable periods after information becomes available during which actions must be taken. Within these windows, we promote early pickup and delivery by introducing small penalty costs that increase with delays.

We adopt an aggregate network modeling approach with one supply node, one depot node, one factory, and one client node. In practice, modular construction logistics networks may involve multiple supply sites, depots, factories, and client locations. Here, we use an aggregate representation to focus on the fundamental interactions between return flows, inventory buffering, and production decisions, while keeping the model tractable and isolating the structural drivers of system performance. Extending the framework to multi-node networks represents a natural direction for future research and would enable the analysis of spatial routing and capacity allocation decisions.
We now describe the characteristics and roles of each node in the logistics network.

Supply: Completed projects return modular units in two quality levels: good (G) and repairable (R). Information on units becomes available in period t and units must be picked up within a lead-time window (L_{S_1}, L_{S_2}). The quality mix depends on deployment conditions, usage intensity, and on-site maintenance practices.

Depot: A central storage facility holding both good-condition units with inventory I_t^G and repairable units with inventory I_t^R, with respective holding costs of H_G and H_R per unit per period. The depot can dispatch units to the factory for repair $(w_{t,f})$ or directly to clients $(w_{t,c})$.

Factory: A dual-purpose facility that renovates repairable units (repair production quantity p_t^R with lead time l_R, and limited by capacity Cap_R) and produces new units (new production quantity p_t^N with lead time l_N, and limited by capacity Cap_N). Factory output can be sent to the depot $(f_{t,d})$ or directly to clients $(f_{t,c})$.

Client: Client orders arrive over time and must be fulfilled within the window (L_{C_1}, L_{C_2}). Deliveries are represented by r_{t_1,t_2}, denoting the number of units delivered in period t_2 for orders revealed in period t_1. Service penalty costs increase with delivery delays, reflecting a preference for earlier delivery. Units that cannot be delivered within the time-window are considered lost sales and are penalized accordingly.

2.1. Notation

We now describe the operational flows and related notation; Table 1 and 2 summarize the decision and state variables, and input parameters for the mathematical model which will be further explained in Section 3. The planning horizon is discretized into T periods, with generic period denoted by t. All flow and production variables in the model represent *quantities per discrete time period* rather than continuous production rates.

Variables	Description
$y^G_{t,t+k,j}$	Number of good quality units available at Supply in period t and shipped in period $t+k$ to destination $j \in \{d, c\}$
$y^R_{t,t+k,j}$	Number of repairable units available at Supply in period t and shipped at $t+k$ to destination $j \in \{d, f\}$
$r_{t,t+k}$	Units delivered to the client in period $t+k$, corresponding to demand ordered in period t
ls_t	Lost sales: units ordered in period t not delivered within time-window
$f_{t,j}$	Number of units leaving Factory during period t to destination $j \in \{d, c\}$
$w_{t,j}$	Number of units leaving Depot in period t to destination $j \in \{f, c\}$
p^q_t	Production started in period t with lead time l_q, $q \in \{N, R\}$
I^q_t	Depot inventory of quality $q \in \{G, R\}$ at the start of period t

Table 1: Decision and state variables

In period t, supply returns $S_t = (G_t, R_t)$ consist of G_t good units (immediately reusable) and R_t repairable units (requiring factory processing). Units must be picked up within (L_{S_1}, L_{S_2}) periods. Early pickup incurs a low service cost $S_s(L_{S_1})$, while later pickup increases cost but may improve demand coordination.

Parameters	Description
$S_t = (G_t, R_t)$	Supply quantities available in period t with pickup window (L_{S_1}, L_{S_2})
D_t	Client demand in period t with delivery window (L_{C_1}, L_{C_2})
H_q	Holding cost per unit per period at depot for quality $q \in \{G, R\}$
$C_{o,j}$	Transportation cost per unit from $o \in \{s, d, f\}$ to $j \in \{d, f, c\}$
$S_s(t)$	Service cost for pickup t periods after arrival, $t \in [L_{S_1}, L_{S_2}]$
$S_c(t)$	Service cost for delivery t periods after request, $t \in [L_{C_1}, L_{C_2}]$
B	Lost sales penalty per unit
Cap_N	Maximum new production capacity per period
Cap_R	Maximum repair capacity per period

Table 2: Input parameters and cost coefficients

Good units available at the Supply in period t can route to the depot $(y^G_{t,t+k,d})$ or directly to clients $(y^G_{t,t+k,c})$ in period $t+k$. Repairable units becoming available at Supply in period t can be shipped to Depot for storage $(y^R_{t,t+k,d})$ or shipped directly to the Factory $(y^R_{t,t+k,f})$ in period $t+k$. The Factory operates in two modes: *renovation* and *new production*. It receives repairable units from the Depot $(w_{t,f})$ or Supply $(y^R_{t,t+k,f})$, and renovates them with a lead time of l_R under repair capacity Cap_R, thus outputting repaired units (p^R_t) in period $t + l_r$. *New production* manufactures $(p^N_t \leq Cap_N)$ units with a lead time of l_N, delivering in period $t + l_N$.

The depot inventory of good units I^G_t increases through inflows from supply $(y^G_{k,t-1,d})$ and factory output $(f_{t-1,d})$, and decreases due to shipments to clients $(w_{t-1,c})$. The depot inventory of repairable units I^R_t increases with returned supply units $(y^R_{k,t-1,d})$ and decreases through shipments to the factory for refurbishment $(w_{t-1,f})$.

Transportation cost matrix $C_{o,j}$ defines the costs between origins $o \in \{s, d, f\}$ and destinations $j \in \{d, f, c\}$.

The objective is to minimize total system costs with respect to routing and production decisions, including transportation, service penalties (supply pickup and client delivery), depot holding costs, and lost sales penalties over a fixed number of T periods.

3. Mathematical Formulation

We consider a finite discrete planning horizon $t = 1, \dots, T$. All supply and demand realizations and their lead-time windows are known in advance (full information). The aggregate cost minimization problem is defined by the objective function in Equation (1).

$$
\begin{aligned}
\min\ Z \ =\ & \sum_t \sum_{k=L_{S_1}}^{L_{S_2}} \Big[(C_{S,D} + S_s(k))\, y^G_{t,t+k,d} \\
& \qquad + (C_{S,D} + S_s(k))\, y^R_{t,t+k,d} \\
& \qquad + (C_{S,F} + S_s(k))\, y^R_{t,t+k,f} \\
& \qquad + (C_{S,C} + S_s(k))\, y^G_{t,t+k,c} \Big] \\
& + \sum_t \Big[C_{D,F}\, w_{t,f} \\
& \qquad + C_{D,C}\, w_{t,c} \\
& \qquad + C_{F,D}\, f_{t,d} \\
& \qquad + C_{F,C}\, f_{t,c} \\
& \qquad + H_G\, I^G_t + H_R\, I^R_t \Big] \\
& + \sum_t \sum_{k=L_{C_1}}^{L_{C_2}} S_c(k)\, r_{t,t+k} \ +\ \sum_t B\, ls_t .
\end{aligned} \tag{1}
$$

The first group of terms captures transportation and pickup service costs for supply returns, accounting for routing decisions of good and repairable units and pickup delays. The second set of terms represents transportation costs for shipments from the depot and the factory, as well as holding costs for good and repairable inventory at the depot. The third set of terms accounts for delivery service penalties associated with delayed client deliveries, while the final term penalizes lost sales for demand not satisfied within the delivery time window.

The model is subject to the following constraints.

Inventory balance at the depot. The depot inventory for each quality class evolves over time based on inflows and outflows, as described by constraints (2) and (3). For good-quality units, inventory increases from units arriving from supply and units completed at the factory, and decreases from shipments to clients. For repairable units, inventory increases from returned supply units and decreases from shipments to the factory for renovation.

$$
I^G_t = I^G_{t-1} - w_{t-1,c} + f_{t-1,d} + \sum_{k=t-1-L_{S_2}}^{t-1-L_{S_1}} y^G_{k,t-1,d} \quad \forall t \tag{2}
$$

$$
I^R_t = I^R_{t-1} - w_{t-1,f} + \sum_{k=t-1-L_{S_2}}^{t-1-L_{S_1}} y^R_{k,t-1,d} \quad \forall t \tag{3}
$$

Depot outflow feasibility. Shipments from the depot cannot exceed the available inventory in each period, as enforced by constraints (4) and (5).

$$
w_{t,c} \le I^G_t \qquad \forall t \tag{4}
$$

$$
w_{t,f} \le I^R_t \qquad \forall t \tag{5}
$$

Factory constraints. Production variables p^N_t and p^R_t represent the number of units whose processing starts in period t. Lead times are deterministic and batch-based, such that all units started in period t become available after l_N or l_R periods. Constraint (6) links the input and output of the factory. The repair input constraint (7) links repair production to incoming repairable units from both the depot and the supply. Repair is assumed to start immediately upon receipt of repairable units. The capacity constraints (8) and (9) limit new and repair production to the available manufacturing capacities.

$$
f_{t,d} + f_{t,c} = p^N_{t-l_n} + p^R_{t-l_r} \qquad \forall t \tag{6}
$$

$$
p^R_t = w_{t,f} + \sum_{k=t-L_{S_2}}^{t-L_{S_1}} y^R_{k,t,f} \qquad \forall t \tag{7}
$$

$$
p^N_t \le Cap_N \qquad \forall t \tag{8}
$$

$$
p^R_t \le Cap_R \qquad \forall t \tag{9}
$$

Supply flow constraints. All supply units returning at time t must be allocated to a destination within their pickup window, as enforced by constraints (10) and (11). Good units can be sent to the depot or directly to clients, while repairable units can be sent to the depot or the factory. These constraints ensure the complete allocation of returned units within the admissible pickup time window.

$$
\sum_{k=L_{S_1}}^{L_{S_2}} \left(y^G_{t,t+k,d} + y^G_{t,t+k,c} \right) = G_t \qquad \forall t \tag{10}
$$

$$
\sum_{k=L_{S_1}}^{L_{S_2}} \left(y^R_{t,t+k,d} + y^R_{t,t+k,f} \right) = R_t \qquad \forall t \tag{11}
$$

Demand and service constraints. Client demand must either be satisfied within the delivery window or counted as lost sales, as enforced by constraint (12). The demand fulfillment constraint(13) ensures that deliveries made in each period match the sum of units shipped from all possible sources (depot, factory, and direct from supply) for orders placed in previous periods. This constraint links order-based delivery decisions to physical flows arriving

Table 3: Parameter options for numerical experiments

Parameter	Option 1	Option 2	Option 3
Holding cost H^G ($H^R = 0.8H^G$)	2	5	10
Service penalty multiplier (pickup) s_s	0.5	1	1.5
Service penalty multiplier (delivery) s_c	0	0.5	1
Lost sales cost B	200	500	–
Demand distribution	TS	1.2 TS	1.5 TS
C_{apN}	$TD - TS + 2$	$TD - TS + 4$	$TD - TS + 8$
C_{apR}	$TR + 2$	$TR + 4$	$TR + 8$
Lead-time windows	S, D : 3–4	S, D : 3–5	S, D : 3–6

at the client in period t.

$$\sum_{k=L_{C_1}}^{L_{C_2}} r_{t,t+k} + ls_t = D_t \qquad \forall t \tag{12}$$

$$\sum_{k=L_{C_1}}^{L_{C_2}} r_{t-k,t} = w_{t,c} + f_{t,c} + \sum_{k=L_{S_1}}^{L_{S_2}} y^G_{t-k,t,c} \qquad \forall t \tag{13}$$

Non-negativity. All decision variables must be non-negative, ensuring the physical feasibility of the solution, as enforced by constraint (14). When using the quality index $q \in \{G, R\}$, the flows from supply to the depot and the factory can be compactly written as $y^q_{t,t+k,j}$, and non-negativity applies to the relevant quality q and destination j.

$$y^G_{t,t+k,j},\ y^R_{t,t+k,j},\ r_{t,t+k},\ f_{t,j},\ w_{t,j},\ p^q_t,\ I^q_t,\ ls_t \geq 0 \qquad \forall t,k,q,j. \tag{14}$$

4. Numerical Experiments

In this section, we analyze how supply and demand variability, capacity constraints, holding and service cost structures, and lead-time flexibility influence system performance in a circular modular construction logistics network. We focus on routing patterns, depot inventory levels, service delays, and lost sales.

All experiments are conducted under a full-information setting in which future supply returns and client orders are known at the beginning of the planning horizon.

Table 4: Transportation costs per unit

from/to	Depot	Factory	Client
Supply	60	70	80
Depot	–	20	60
Factory	20	–	70

4.1. Experimental Design

Supply returns quantities consist of good (G) and repairable (R) units and follow either uniform or lumpy distributions. Client demand is generated independently but follows the same distributional *type* (uniform or lumpy) as supply within each considered scenario to ensure comparability across variability regimes. The lumpy distribution, denoted by $L(p, N)$, captures occasional clustered arrivals (or demand) with large batches of size N that occur with probability p, and are associated with larger construction projects. The lumpy distribution is added to the uniform distribution. Supply and demand arrive according to discrete-time arrival processes. At each period t, supply returns become available in quantities (G_t, R_t), where these quantities are stochastic and are drawn independently across periods from the specified distributions. Based on the supply distribution, we consider two cases:

Case 1 (Uniform Supply). Supply returns of good (G) and repairable (R) units follow uniform distributions $U(0, 20)$ and $U(0, 10)$, respectively. This case represents a relatively stable operating environment with moderate variability.

Case 2 (Lumpy Supply). Supply returns follow lumpy distributions, $U(0, 10) + L(0.1, 40)$ for good units and $U(0, 6) + L(0.1, 20)$ for repairable units. Here $L(p, N)$ denotes a lumpy distribution where a batch of size N occurs with probability p in a given period and zero otherwise. In our experiments, we set $p = 0.1$, with batch sizes $N = 40$ for good units and $N = 20$ for repairable units. This case reflects a stressed but realistic operating environment commonly observed in temporary modular construction projects.

We consider three different options (*option 1, option 2 and option 3*) for the demand levels (with respect to total supply TS) and the values of model parameters related to production capacities, holding costs, service penalties, and lead-time windows, as indicated in Table 3. Holding costs H^R are proportional to H^G, as are the customer service costs:

$$S_c(k) = s_c \cdot H^G(k - L_{C_1}),$$

with a similar expression for the supply service costs. Transportation costs are given in Table 4 and are assumed to be quality independent. Demand arrivals follow the same modeling structure as supply, with per-period quantities drawn from the specified distribution and scaled relative to the realized total supply TS over the planning horizon. In particular, option 1, with demand equal to total supply TS, corresponds to a balanced setting in which expected total demand equals ex-

Table 5: Base configuration: performance metrics under uniform (Case 1) and lumpy (Case 2) supply

Metric	Case 1 (Uniform) Avg.	Case 1 (Uniform) Std.	Case 2 (Lumpy) Avg.	Case 2 (Lumpy) Std.
Routing volumes				
Good units to depot ($S \to D$)	1	3	32	37
Good units to client ($S \to C$)	483	38	438	59
Repairable units to depot ($S \to D$)	33	23	86	59
Repairable units to factory ($S \to F$)	198	31	147	37
Good units from depot to client ($D \to C$)	17	4	62	33
Repairable units from depot to factory ($D \to F$)	10	9	32	24
Good units from factory to depot ($F \to D$)	2	4	29	25
Good units from factory to client ($F \to C$)	344	82	309	102
Costs				
Transport cost	79 782	6 172	78 970	8 614
Holding cost	1 088	841	5 915	5 410
Service cost	1 704	400	2 557	551
Lost sales cost	430	1 783	17 740	28 764
Inventory and service				
Total inventory (G)	81	36	439	486
Total inventory (R)	297	315	1 436	1 363
Maximum inventory	33	21	103	69
Avg. pickup delay from Supply (S)	0.26	0.12	0.51	0.10
Avg. delivery delay to Client (C)	0.39	0.13	0.41	0.38

pected total supply, while options 2 and 3, where demand is scaled at 1.2 TS and 1.5 TS, represent increasingly demand-intensive regimes. New production capacity is defined relative to the gap between total demand (TD) and total supply (TS), with additional slack as specified in Table 3. Repair capacity is defined relative to the total volume of returned units that require repair, TR, along with additional slack.

In the following, we first analyze Case 1 and Case 2 under parameter *option 2* in Table 3, which serves as a base configuration. Then, to investigate the effects of parameter changes on system performance, we conduct a sensitivity analysis in which, for both Case 1 and Case 2, the model parameters are varied one by one and take the values under *options 1* and *3* , as indicated in Table 3

4.2. Results

We first present the results for Case 1 and Case 2 under parameter option 2 in Table 5, highlighting clear differences between the two supply regimes.

Under uniform returns, most good units are delivered directly to clients, while repairable units are primarily routed to the factory. Depot usage remains limited, resulting in low inventory levels, short pickup and delivery delays, and negligible lost sales. Flexible pickup and delivery lead-time windows act as a temporal buffer that aligns supply with demand and typically avoids the need for depot storage.

Under lumpy returns, routing through the depot increases substantially, highlighting its role as a buffer under clustered arrivals. This leads to higher average and peak inventory levels, longer pickup delays, and significantly higher lost sales. These effects occur despite only moderate increases in transportation and service costs, indicating that variability plays a dominant role in system performance and makes depot storage operationally valuable.

These results indicate that, under uniform return patterns, the availability of flexible pickup and delivery lead-time windows creates a temporal buffer that is typically sufficient to coordinate supply and demand without relying on depot storage.

We conduct a sensitivity analysis to assess how changes in demand, cost parameters, lead-time flexibility, and capacity settings affect routing decisions, inventory dynamics, service performance, and lost sales under uniform and lumpy return patterns. Figure 2 shows the effect of unit holding cost levels under uniform and lumpy return patterns. Under uniform returns, higher holding costs reduce average inventory levels, reflecting a shift toward more direct routing and less storage at the depot. Under lumpy returns, inventory levels remain high

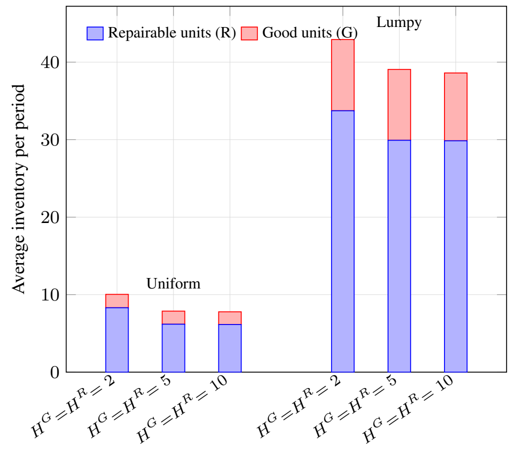

Figure 2: Effect of holding cost (H^G, H^R) on average inventory under uniform and lumpy returns.

and are much less sensitive to changes in holding costs, indicating that the depot primarily functions as a structural buffer under clustered arrivals. Table 6 shows that

Table 6: Effect of supply-side service penalty multiplier (s_s) on average inventory levels and pick-up delay from Supply S under uniform and lumpy return patterns.

Uniform			
s_s	Avg. inv G	Avg. inv R	Avg. Pick-up delay from S
0.5	1.58	3.54	0.51
1.0	1.69	6.19	0.26
1.5	2.15	7.38	0.15
Lumpy			
s_s	Avg. inv G	Avg. inv R	Avg. Pick-up delay from S
0.5	8.15	24.60	0.94
1.0	9.15	29.92	0.51
1.5	10.79	31.63	0.31

service penalty levels have a fundamentally different impact under uniform and lumpy return patterns. Under uniform returns, increasing service penalties significantly reduce pickup delays, increase delivery delays, and lead to higher inventory levels, indicating an active trade-off between timing and storage decisions. Under lumpy returns, service penalties mainly reallocate delays between supply pickup and client delivery, while inventory levels and lost sales remain largely unchanged. This suggests that service pricing can influence timing decisions but cannot resolve structural shortages caused by highly irregular supply. Table 7 shows that delivery-side service

Table 7: Effect of delivery-side service penalty multiplier (s_c) on average inventory levels and delivery delay to Client C under uniform and lumpy return patterns.

Uniform			
s_c	Avg. inv G	Avg. inv R	Avg. Delivery delay to C
0.0	1.63	6.44	0.70
0.5	1.69	6.19	0.39
1.0	1.73	6.44	0.31
Lumpy			
s_c	Avg. inv G	Avg. inv R	Avg. Delivery delay to C
0.0	8.66	31.22	0.52
0.5	9.14	29.91	0.41
1.0	9.39	29.39	0.35

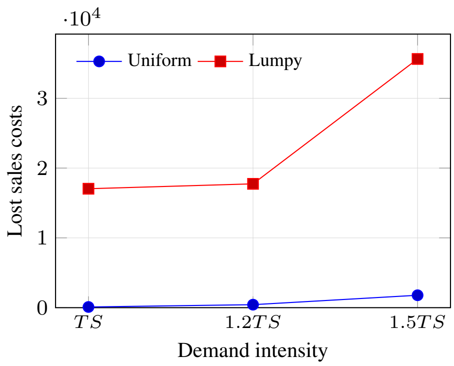

Figure 3: Lost sales costs as a function of demand intensity under uniform and lumpy return patterns.

penalties have little effect on inventory levels under both return patterns. Increasing s_c mainly reduces client delivery delays, indicating that lead-time penalties influence timing decisions without affecting inventory dynamics.

Figure 3 presents the evolution of lost sales costs as demand intensity increases from TS to $1.2TS$ and $1.5TS$ under uniform and lumpy return patterns. For uniform returns, lost sales increase gradually with higher demand levels. In contrast, under lumpy returns, lost sales are substantially higher across all demand levels and increase sharply as demand intensifies. The gap between the two regimes widens as demand increases, indicating a markedly different system response.

Figure 4 shows the effect of production capacity expansion on lost sales costs under uniform and lumpy return patterns. For convenience, we indicate with PC the base capacity, which is $PC = TD - TS$ for new production capacity, and $PC = TR$ for repair capacity, to which we then add a slack as indicated in Table 3. Under uniform returns, a moderate capacity increase from PC+2 to PC+4 already reduces lost sales almost to zero, and a further expansion to PC+8 eliminates lost sales entirely. Under lumpy returns, capacity expansion also substantially reduces lost sales, but even at PC+8 the system still experiences considerable unmet demand. This indicates that additional capacity is effective in mitigating shortages; however, irregular return patterns limit the extent to which capacity alone can restore service performance.

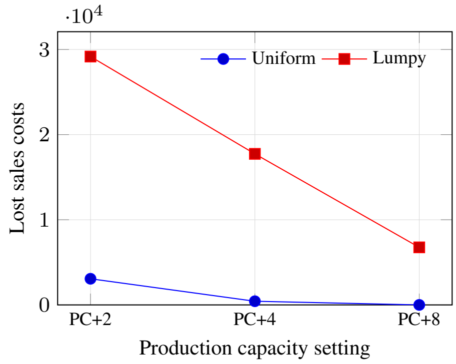

Figure 4: Effect of production capacity expansion on lost sales costs under uniform and lumpy return patterns.

Figure 5 presents the effect of delivery lead-time flexibility on lost sales costs under uniform and lumpy return patterns. Under uniform returns, extending the delivery window from the base case to $(3, 6)$ entirely eliminates lost sales, while a tighter window $(3, 4)$ increases lost sales. Under lumpy returns, lost sales remain high but decrease noticeably when the delivery window is extended to $(3, 6)$, indicating that lead-time flexibility mitigates feasibility loss without fully eliminating it.

Increasing repair capacity has only a marginal effect on lost sales under both uniform and lumpy return patterns, indicating that repair capacity is not a binding constraint in the analyzed settings. While lower penalty val-

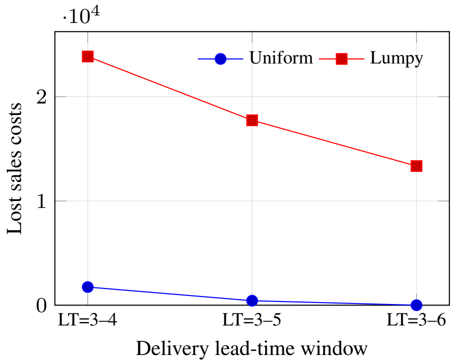

Figure 5: Effect of delivery lead-time flexibility on lost sales costs under uniform and lumpy return patterns.

ues lead to substantially lower lost sales costs , the actual lost sales level, inventory levels, routing decisions, and delays remain largely unchanged. This indicates that a further reduction of the unit lost sales costs would be required to have a substantial influence on the performance.

5. Conclusions

This paper develops a discrete-time, time-expanded optimization model for a centralized modular construction logistics network with circular flows. The model explicitly distinguishes between good-quality and repairable units, incorporates pickup and delivery lead-time windows through time-dependent service penalties, and captures the interactions between depot storage, factory renovation, and new production under capacity constraints. Demand that cannot be met within its delivery window is modeled as lost sales, enabling an explicit assessment of service performance. Using this formulation, we conduct a numerical study comparing uniform and lumpy return patterns and analyzing the impact of key parameters. Under uniform returns, flexible lead-times act as a temporal buffer, supporting direct routing and resulting in low depot usage, inventories, and lost sales. Under lumpy returns, the depot becomes a critical structural buffer, with substantially higher routing through the depot, inventory levels, and lost sales despite only moderate cost changes. Sensitivity analyzes show that holding and service costs mainly affect timing and inventory decisions, whereas demand intensity, production capacity, and delivery lead-time flexibility have a stronger impact on lost sales. Overall, the results clarify when centralized depot storage is economically justified and highlight the operational value of lead-time flexibility in circular modular construction supply chains.

Several extensions provide directions for future research. In practice, the assumption of full information may not hold, since future supply returns and client orders are typically uncertain. The proposed model could therefore be embedded in a rolling-horizon decision framework in which the optimization is periodically re-solved as new information becomes available and forecasts are updated. Incorporating uncertainty in returns, demand, and processing times within such a rolling-horizon framework would improve realism and robustness. Furthermore, the current formulation adopts an aggregate network representation to provide structural insights while keeping the model computationally tractable. Extending the model to multiple suppliers, depots, factories, and client locations would allow spatial effects and capacity allocation decisions to be studied. In such larger network settings, heuristic or decomposition-based methods could be employed to scale the approach and support real-time operational planning.

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