ASEAN International Sandbox Conference 2026
http://aseansandbox.org

AISC Proceedings, Volume 11, 2026

A General Linear Programming Framework for Construction Material Transportation Planning with a Simplex-Based Illustrative Case

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Abstract

Construction material transport planning must integrate supply, schedule-driven demand, capacity, inventory, and environmental considerations beyond a basic origin-destination matrix. This study develops a transparent linear-programming (LP) baseline, proves the classical transportation model is a nested special case, and identifies which extensions remain linear. A multi-source, multi-site, multi-material, multi-period LP is formulated. A 2-depot/2-site case is solved by two-phase simplex and cross-checked with Excel Solver; a synthetic 2 x 2 x 2 x 2 stress test activates inventory, capacity, and an emission cap. The hand-worked case yields $x_1 = 5$, $x_2 = 30$, $x_3 = 20$, and $x_4 = 0$ at 13.5 million VND/day; one additional m^3/day of Depot B capacity lowers cost by 0.2 million VND while the basis remains optimal. In the stress test, an 820 kg CO2e emission cap reduces modeled emissions from 835.25 to 820 kg while monetary cost rises from 6.489 to 6.5262 million VND. The contribution is structural rather than algorithmic: an auditable LP bridge from classical transportation to integrated construction logistics, with explicit boundaries to MILP and stochastic extensions. The numerical results demonstrate computational consistency, not empirical savings; project-level calibration remains necessary.

Keywords: *construction logistics, linear programming, transportation planning, simplex method, material flow, sustainability*

1. Introduction

Construction material transportation is a central component of project logistics because delivery cost, timing, site congestion, and material availability directly affect the continuity of construction operations. Classical transportation and network-flow models provide a transparent minimum-cost allocation structure, but their standard origin-destination form does not by itself represent time-phased demand, multiple material types, inventory carryover, temporary receiving restrictions, or schedule-dependent site conditions (Dantzig & Thapa, 1997; Hillier & Lieberman, 2021; Taha, 2017; Tran & Nguyen, 2026). Consequently, a model can be mathematically correct as a transportation problem while remaining too narrow for construction-logistics decision support.

Construction-logistics research has progressively widened this scope. Caron, Marchet, and Perego (1998) connected project logistics with procurement and construction processes. Said and El-Rayes (2011, 2014) integrated procurement, storage, site constraints, and multi-objective planning, while Nolz (2021) coordinated construction schedules with material deliveries. Son, Duy, and Dat (2021) linked logistics planning to material-cost optimization, and Awaad, Mansour, Mahdi, and Abdelrasheed (2024) emphasized supply-chain integration and productivity. Reviews and applied frameworks similarly show that transportation decisions are embedded in a broader supply-chain system rather than functioning as isolated haulage choices (Alanazi, Al-Gahtani, & Alsugair, 2022; Rehman, Chaabane, & Khan, 2021).

Sustainability and resilience add another modeling layer. Guerlain, Renault, and Ferrero (2019) showed the environmental significance of urban construction logistics; Zhang, Peng, Yuan, and Ping (2023) quantified carbon emissions during the logistics and transportation stage of prefabricated buildings; and Shen, Zhang, Sun, Yang, and Li (2025) incorporated complex environmental settings into multiperiod location-allocation decisions. More recently, Chen, Hammad, Alyami, and Haddad (2025) combined environmental objectives with disruption resilience through stochastic programming. These advances strengthen realism but also increase data requirements and computational complexity.

More specifically, the closest optimization formulations differ in both decision scope and mathematical structure. Said and El-Rayes (2011) jointly optimized procurement and on-site storage using a genetic-algorithm model, and their 2014 AMCLOS system linked supply and site logistics with schedule/BIM data and multi-objective optimization. Nolz (2021) coordinated tactical scheduling with operational material deliveries through hierarchical mixed-integer and inventory-routing models. Shen et al. (2025) addressed multiperiod construction-logistics-center location-allocation with transportation risk using a hybrid nonlinear integer model, while Chen et al. (2025) modeled sourcing, inventory, and trans-shipment under disruption uncertainty through multi-objective two-stage stochastic programming. In contrast, the present study deliberately retains an LP core: its purpose is not

to supersede these richer formulations, but to provide an auditable baseline in which the classical transportation model is recovered exactly and the point at which binary, nonlinear, or stochastic extensions become necessary is explicit.

The resulting research gap is therefore not an absence of transportation optimization or simplex theory. Rather, there is value in an explicitly nested LP framework that connects three levels of analysis: a general construction-material flow formulation with practically relevant linear constraints; a formal reduction to the classical transportation model; and a clear boundary between extensions that remain linear and those that require mixed-integer, robust, stochastic, or multi-objective optimization. Such a baseline is useful because it is auditable, interpretable through reduced costs and shadow prices, and easy to calibrate before more complex features are added.

This study addresses that gap by developing a deterministic LP framework for construction material transportation and checking its internal logic with reproducible analytical and computational examples. The scientific contribution is structural and methodological rather than algorithmic: the simplex method is used as a transparent solution device, while the contribution lies in the construction-logistics nesting relation, the explicit integration of supply, material balance, route and receiving capacities, and inventory, and the disciplined delineation of linear and richer extensions.

2. Objectives

1) Formulate a deterministic LP framework that integrates source availability, schedule-driven demand, route capacity, site receiving capacity, inventory carryover, and optional linear environmental cost for construction material transportation.
2) Demonstrate analytically that the classical one-material, one-period transportation problem is a nested special case of the general formulation and verify a representative 2 x 2 instance using the two-phase simplex method and Excel Solver.
3) Evaluate the managerial interpretation, practical calibration requirements, sustainability options, and methodological limits of the framework to identify concrete priorities for project-level empirical validation.

3. Materials and Methods

3.1 Modeling scope and notation

The study used a model-development design with analytical and computational verification. Let I denote the set of depots or suppliers, J the set of construction sites, M the set of material types, and T the set of planning periods. The primary decision variables are x_{ijmt}, the quantity of material m transported from source i to site j in period t, and q_{jmt}, the end-of-period inventory of material m at site j. Table 1 defines the principal symbols used in the formulation.

The formulation assumes deterministic coefficients, divisible nonnegative flows, and linear cost and capacity relationships within each planning period. Initial inventory q_{jm0} is treated as known. When different materials use different physical units, $kappa_m$ converts one unit of material m into a common route or handling-capacity equivalent so that aggregate capacity constraints remain dimensionally interpretable. The coefficient c_{ijmt} is a generalized variable logistics cost per transported unit: depending on project accounting, it may include vehicle operating cost, fuel, driver labor, loading and unloading, tolls, and route-specific handling charges to the extent that these costs vary linearly with shipped quantity. Fixed mobilization, route-opening, or subcontractor activation charges are excluded from c_{ijmt} and require the MILP extension described in Section 4.4.

Table 1 Main notation used in the general formulation

Symbol	Definition
I, J, M, T	Sets of sources, construction sites, materials, and planning periods
x_{ijmt}	Quantity of material m shipped from source i to site j in period t
q_{jmt}	End-of-period inventory of material m at site j
c_{ijmt}	Generalized variable transport/logistics cost per unit
h_{jmt}	Unit inventory holding cost
S_{imt}	Available supply of material m at source i in period t
D_{jmt}	Required demand of material m at site j in period t

U_{ijt}	Route or transport capacity in period t, in common capacity units
R_{jt}	Site receiving or handling capacity in period t
H_{jmt}	Storage capacity for material m at site j
$kappa_m$	Capacity-equivalent conversion factor for material m
e_{ijmt}	Route-specific emission factor per transported unit
tau	Carbon price or monetary weight per emission unit

3.2 General linear-programming formulation

The monetary-cost objective minimizes transportation and on-site inventory holding cost across all sources, sites, materials, and periods:

$$\min Z = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} c_{ijmt}\, x_{ijmt} + \sum_{j\in J}\sum_{m\in M}\sum_{t\in T} h_{jmt}\, q_{jmt}$$

The model is subject to source-availability, material-balance, route-capacity, site-receiving, storage, and nonnegativity constraints:

$$\sum_{j\in J} x_{ijmt} \le S_{imt}, \qquad \forall i \in I,\ m \in M,\ t \in T$$

$$q_{jm,t-1} + \sum_{i\in I} x_{ijmt} = D_{jmt} + q_{jmt}, \qquad \forall j \in J,\ m \in M,\ t \in T$$

$$\sum_{m\in M} \kappa_m\, x_{ijmt} \le U_{ijt}, \qquad \forall i \in I,\ j \in J,\ t \in T$$

$$\sum_{i\in I}\sum_{m\in M} \kappa_m\, x_{ijmt} \le R_{jt}, \qquad \forall j \in J,\ t \in T$$

$$0 \le q_{jmt} \le H_{jmt}, \qquad x_{ijmt} \ge 0$$

The first constraint limits dispatches by source availability. The material-balance equation connects deliveries to schedule-driven demand and carryover inventory. Route and site capacities are expressed in common capacity-equivalent units through $kappa_m$, and the final bounds enforce inventory feasibility and nonnegativity. Because all relationships are linear, additional verified linear procurement charges, holding penalties, or time-window costs can be incorporated without changing the LP class.

A preliminary environmental cost can also remain inside the LP. With route-specific emission factor e_{ijmt} and carbon price or policy weight tau, the transport coefficient can be replaced by:

$$\tilde{c}_{ijmt} = c_{ijmt} + \tau e_{ijmt}$$

This substitution internalizes a linear carbon cost without changing the feasible region. Alternatively, total emissions can be constrained by a linear cap, as discussed in Section 4.4.

3.3 Nested classical transportation case and solution procedure

For one homogeneous material and one planning period, set |M| = |T| = 1, fix initial and terminal inventory at zero, and treat route and receiving capacities as nonbinding. Let x_{ij} be the quantity transported from depot i to site j, c_{ij} the unit transportation cost, S_i the available supply, and d_j the exact demand. The general formulation then reduces to:

$$\min Z = \sum_{i}\sum_{j} c_{ij}\, x_{ij}$$

$$\sum_{j} x_{ij} \le S_i, \qquad \forall i$$

$$\sum_{i} x_{ij} = d_j, \qquad \forall j$$

$$x_{ij} \ge 0, \qquad \forall i, j$$

Under these restrictions, the inventory term vanishes, material balance becomes exact destination demand, and the route and receiving constraints drop out. The classical transportation model is therefore a nested

restriction of the broader construction-logistics formulation. This explicit reduction is the central methodological linkage of the paper.

The illustrative case was solved using the two-phase simplex method because exact-demand equations require artificial variables to construct an initial feasible basis. Phase I minimized artificial-variable infeasibility, and Phase II restored the original cost objective after feasibility was established. The final analytical result was then cross-checked in a separate Microsoft Excel implementation using the Simplex LP engine, which is appropriate for a continuous model with a linear objective and linear constraints (Microsoft Support, n.d.). This cross-check verifies numerical consistency of the same deterministic formulation; it is not empirical validation.

4. Results and Discussion

4.1 Illustrative case and simplex result

A two-depot/two-site network was selected as the smallest nontrivial instance in which each site could be served from more than one source, route costs competed, and available capacity exceeded but did not exactly equal total demand. The instance remained small enough for complete manual inspection of the simplex logic. Depot A supplied at most 40 m^3/day and Depot B at most 20 m^3/day. Site I required exactly 25 m^3/day and Site II exactly 30 m^3/day. Unit transportation costs were 400, 250, 200, and 350 thousand VND/m^3 on routes A-I, A-II, B-I, and B-II, respectively. Figure 1 summarizes this network and makes the cost trade-offs visible before optimization.

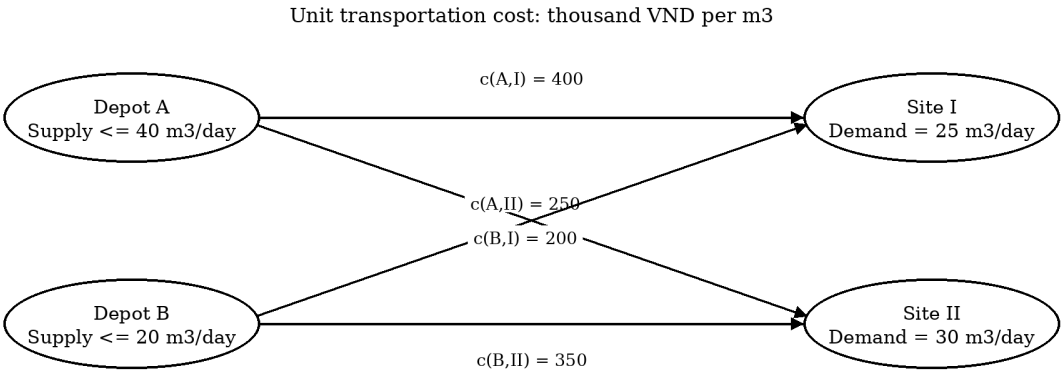


Figure 1 Illustrative two-depot/two-site transportation network and route unit costs

Let x_1, x_2, x_3, and x_4 denote shipments on routes A-I, A-II, B-I, and B-II, respectively. Under a single-period, no-inventory, continuous-flow, and no-fixed-cost setting, the instantiated model was:

$$\min Z = 400x_1 + 250x_2 + 200x_3 + 350x_4$$
$$x_1 + x_2 \leq 40$$
$$x_3 + x_4 \leq 20$$
$$x_1 + x_3 = 25$$
$$x_2 + x_4 = 30$$
$$x_1, x_2, x_3, x_4 \geq 0$$

Introducing slack variables s_1 and s_2 for the supply constraints and artificial variables a_1 and a_2 for the demand equations gave the Phase I standard form:

$$x_1 + x_2 + s_1 = 40$$
$$x_3 + x_4 + s_2 = 20$$
$$x_1 + x_3 + a_1 = 25$$
$$x_2 + x_4 + a_2 = 30$$
$$\max P = -a_1 - a_2$$

Phase I eliminated both artificial variables and reached an auxiliary objective value of zero, establishing feasibility. Phase II then restored the original cost coefficients. The resulting optimal tableau is reported in Table 2; the reduced-cost row Cj - Zj was nonnegative for the nonbasic variables, confirming optimality for the minimization problem.

Table 2 Optimal Phase II simplex tableau

C_B	Basic	x_1	x_2	x_3	x_4	s_1	s_2	RHS
250	x_2	0	1	0	1	0	0	30
0	s_1	0	0	0	0	1	1	5
400	x_1	1	0	0	-1	0	-1	5
200	x_3	0	0	1	1	0	1	20
	Cj - Zj	0	0	0	300	0	200	

The basic variables were $x_2 = 30$, $s_1 = 5$, $x_1 = 5$, and $x_3 = 20$, with all other decision variables nonbasic. The optimal transportation plan and objective value were therefore:

$$x_1 = 5, \quad x_2 = 30, \quad x_3 = 20, \quad x_4 = 0$$
$$Z_{\min} = 400(5) + 250(30) + 200(20) + 350(0) = 13{,}500$$

Thus, the minimum transportation cost was 13.5 million VND/day. Depot B was fully assigned to Site I because route B-I was the least-cost route in the network, while Depot A served the remaining 5 m^3/day at Site I and the full 30 m^3/day at Site II. The allocation used the scarce Depot B capacity where its cost advantage over Depot A was largest: B-I was 200 thousand VND/m^3 cheaper than A-I, whereas A-II was already 100 thousand VND/m^3 cheaper than B-II.

4.2 Solver consistency check and managerial interpretation

The Excel Solver implementation reproduced the simplex solution exactly and therefore served as a numerical consistency check. Table 3 combines feasibility checks with the most decision-relevant sensitivity information from the final basis. Both demand equations were binding, Depot B was fully utilized, and Depot A retained 5 m^3/day of slack. The local simplex multipliers for the constraint order Supply A, Supply B, Demand I, and Demand II were:

$$(\pi_{S_A}, \pi_{S_B}, \pi_{D_I}, \pi_{D_{II}}) = (0, -200, 400, 250) \quad \text{thousand VND per m}^3$$

Table 3 Solver consistency check and local managerial interpretation

Metric	Cross-check result	Interpretation
Optimal plan	x_1=5, x_2=30, x_3=20, x_4=0	Same solution from simplex and Excel Solver
Minimum cost	13,500 thousand VND/day	13.5 million VND/day
Supply A	35 <= 40	Slack = 5 m^3/day
Supply B	20 = 20	Binding capacity
Demand I	25 = 25	Exact requirement met
Demand II	30 = 30	Exact requirement met
Local multiplier: Supply A	0	Extra A capacity has no current marginal value
Local multiplier: Supply B	-200	One extra m^3/day lowers cost by 200 thousand VND while the current basis remains optimal

The zero multiplier for Depot A was consistent with its unused capacity. In contrast, the -200 multiplier for Depot B indicated that, while the current basis remained optimal, one additional m^3/day of B capacity would reduce minimum daily cost by 200 thousand VND by replacing more expensive A-I flow. The positive demand multipliers indicated the local cost of incremental demand. These values translate simplex output into procurement and site-planning information: they identify which capacity bottleneck is economically valuable to relax and where added demand is most costly.

4.3 Multiperiod, multimaterial computational stress test

To exercise dimensions absent from the hand-worked case, a systematically generated 2-source x 2-site x 2-material x 2-period instance (16 shipment variables and 8 inventory variables) was solved under the same LP. For M_1 and M_2, kappa = (1, 0.8) and holding cost was 2 thousand VND per unit-period. Supply [M_1, M_2] at (A, B) was [(45, 35), (25, 25)] in period 1 and [(20, 15), (20, 15)] in period 2; demand at (I, II) was [(25, 20), (20, 15)] and [(30, 25), (25, 20)], respectively. Route capacities (A-I, A-II, B-I, B-II) were (35, 30, 25, 25) and (20, 18, 20, 15), while site receiving limits (I, II) were (60, 50) and (45, 40). Storage limits were 20 units for M_1 and 15 for M_2 at each site. For M_1 in period 1, the route-cost matrix [A-I, A-II; B-I, B-II] was [40, 30; 28, 35] thousand

VND/unit and the emission matrix was [3.0, 2.5; 8.0, 7.0] kg CO2e/unit; M_2 added 5 thousand VND/unit and used 0.9 times the emission factor, while period 2 added 2 thousand VND/unit to cost. These settings made period-2 supply 15 units short of period-2 demand for each material, forcing inventory carryover.

The baseline optimum had a monetary objective of 6.489 million VND and total emissions of 835.25 kg CO2e; end-of-period-1 inventory was 40 units. Five route-capacity constraints and both period-1 receiving limits were binding. Adding the linear cap E <= 820 kg CO2e produced a feasible optimum of 6.5262 million VND with emissions at the cap and period-1 inventory of 30 units. Relative to the baseline, the synthetic cap reduced emissions by 1.83% with a 0.57% increase in the monetary objective. Thus, the same formulation operationally activates multiple materials, multiple periods, inventory carryover, route and receiving capacities, and a linear environmental constraint while remaining within the LP class. This is a computational stress test on synthetic data, not empirical validation or evidence of realized project savings.

4.4 Practical applicability, sustainability, and limitations

The general framework maps directly onto a rolling construction-material planning cycle. Bill-of-quantities and look-ahead schedule data can determine D_{jmt}; supplier and depot records can determine S_{imt}; haulage rates, fleet availability, and access windows can determine c_{ijmt} and U_{ijt}; and site logistics plans can determine R_{jt} and H_{jmt}. The LP can then be re-solved as schedules, inventories, or route conditions change. This implementation logic places transportation optimization inside integrated supply-chain management, consistent with the broader construction-logistics literature (Caron et al., 1998; Nolz, 2021; Said & El-Rayes, 2011, 2014; Awaad et al., 2024).

The continuous transport-flow block contains |I||J||M||T| variables and remains sparse because each flow variable enters only a limited set of supply, balance, route, and site-capacity constraints. The stress test in Section 4.3 demonstrates operation across additional dimensions but not project-scale scalability; computational performance should therefore be demonstrated rather than assumed. A project-level validation should reconstruct the observed dispatch plan, solve the calibrated model over the same horizon, and compare total logistics cost, demand-service feasibility, site congestion or inventory indicators, computational time, and carbon outcomes where reliable data are available.

Sustainability can be incorporated without leaving the LP class when emissions are proportional to transported quantity. With fixed emission factors, total transportation emissions are:

$$E = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} e_{ijmt}\, x_{ijmt}$$

The planner can either internalize emissions through the carbon-adjusted coefficient introduced in Section 3.2 or minimize monetary cost subject to $E <= E_{max}$. Both remain linear. In contrast, a fixed route-opening, mobilization, or subcontractor activation cost requires a binary variable y_{ijt} and changes the problem to mixed-integer linear programming (MILP):

$$\min Z_{\mathrm{MILP}} = Z_{\mathrm{LP}} + \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} F_{ijt}\, y_{ijt}$$

$$\sum_{m\in M} \kappa_m\, x_{ijmt} \le U_{ijt} y_{ijt}, \qquad y_{ijt} \in \{0,1\}$$

This distinction defines the boundary of the simplex-solvable core. Binary route activation requires branch-and-bound or related MILP algorithms, and uncertain demand, supply, travel conditions, or disruption risk motivate robust or stochastic formulations. Such extensions are supported by recent construction-logistics research but require additional data and validation (Chen et al., 2025; Guerlain et al., 2019; Shen et al., 2025; Zhang et al., 2023).

The present study has four limitations. First, linear coefficients do not capture congestion, economies of scale, or nonlinear delay penalties. Second, continuous flows abstract from indivisible truckloads unless an MILP extension is introduced. Third, although Section 4.3 activates multiple periods, materials, dynamic inventory, and capacity constraints, it remains a small systematically generated stress test rather than a field-calibrated project instance. Fourth, the coefficients are deterministic; no claim is made about realized savings, external validity, or large-scale solver performance. These limitations make empirical calibration the decisive next step rather than an optional extension.

5. Conclusion

This study formulated a transparent LP framework that places construction material transportation inside a broader material-flow decision structure. The formulation connects source availability, schedule-driven demand, route capacity, site receiving capacity, inventory carryover, and optional linear environmental cost. Its methodological contribution is the explicit nesting relation: the classical transportation problem is recovered as a restricted case, while carbon pricing or emission caps can remain within LP and fixed route activation moves the model into MILP.

The two-depot/two-site illustration produced the optimal plan $x_1 = 5$, $x_2 = 30$, $x_3 = 20$, and $x_4 = 0$ with a minimum cost of 13.5 million VND/day; a separate Excel Solver implementation reproduced the result as a consistency check. The final basis generated interpretable local marginal values, showing that additional Depot B capacity has economic value whereas unused Depot A capacity does not under the current basis. The additional 2-source x 2-site x 2-material x 2-period stress test activated interperiod inventory, route and receiving capacities, and a linear emission cap; the cap reduced modeled emissions by 1.83% with a 0.57% increase in the synthetic monetary objective. These results demonstrate analytical and computational consistency and managerial interpretability, not empirical project savings. Future work should calibrate the framework using verified project-level logistics, schedule, capacity, cost, and emission data; compare optimized and observed dispatch plans; test sensitivity to uncertainty; and evaluate solver performance as problem dimensionality increases.

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