A Spatial Multi-Criteria Framework for Assessing Last-Mile Delivery Resilience in Modular Construction Supply Chains: A Network-Based Analysis of Lille

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Abstract -

The resilience of construction supply chains has become a critical issue in dense urban environments, particularly for modular construction systems that rely on large and time-sensitive deliveries. While existing studies have extensively addressed construction logistics and supply-chain resilience at strategic and regional levels, the last-mile delivery phase within urban areas remains insufficiently analyzed. This paper proposes a spatially explicit methodological framework to assess last-mile delivery resilience for modular construction in urban contexts. The framework is based on a grid-based, multi-criteria analysis integrating road access suitability, truck-feasible network redundancy, and urban morphology operability. The city of Lille was selected as a representative dense European urban last-mile context and was discretized into a regular grid to ensure spatial comparability and reproducibility. Open geospatial data were used to model road networks and urban form, and normalized indicators were computed for each grid cell. The results showed that, although large portions of the study area remained physically accessible for modular deliveries, the truck-feasible road network exhibited very low redundancy, indicating a high sensitivity to local disruptions. Urban morphology was found to be a secondary limiting factor compared to network structure. The proposed framework enabled the identification of structurally fragile zones and critical corridors, providing a basis for targeted operational, territorial, and regulatory recommendations to improve last-mile delivery resilience for modular construction.

Keywords -

Modular construction; Last-mile delivery; Supply-chain resilience; Urban road networks; GIS-based multi-criteria analysis

1 Introduction

Urban construction systems increasingly face constrained spatial conditions, environmental requirements, and regulatory frameworks. In response, modular construction has gained growing attention as an alternative to conventional methods due to its potential to improve productivity, quality, and sustainability by shifting a significant share of activities from on-site execution to off-site manufacturing [1, 2]. This shift, however, increases project dependency on reliable logistics and precise delivery operations, particularly in dense urban environments.

In this context, the last mile of the construction supply chain—defined as the final segment connecting the urban transport network to the construction site—plays a critical role in project performance. Modular construction relies on transporting large and often oversized components under strict sequencing and time constraints, making last-mile accessibility and reliability decisive factors. Unlike other time-critical construction deliveries such as ready-mixed concrete or crane-assembled components, modular systems impose a compounded constraint: components are dimensionally fixed and non-substitutable, assembly sequences are predetermined and cannot tolerate partial or delayed deliveries, and off-site fabrication schedules are decoupled from the site, eliminating any on-site buffering capacity. A single delivery failure in a modular sequence thus propagates directly to installation downtime, with no on-site workaround available. Urban freight studies consistently identify last-mile operations as the most complex and disruption-prone segment due to congestion, access restrictions, and competition for limited urban space [3], with similar constraints observed in urban construction logistics, where delivery failures directly affect on-site productivity and installation schedules [4].

Supply-chain resilience has been widely studied in manufacturing and logistics and, more recently, in construction, emphasizing the ability of systems to absorb, adapt to, and recover from disruptions. Research on modular and prefabricated supply chains highlights transportation and logistics as critical determinants of resilience [2, 5]. However, most contributions remain project-centric or conceptual and rarely translate resilience principles into spatially explicit indicators applicable at the urban scale.

In parallel, geographic information systems (GIS) and multi-criteria decision analysis (MCDA) have been widely used in urban planning and infrastructure assessment to integrate heterogeneous spatial data within transparent and reproducible frameworks [6, 7]. Three GIS capabilities are central to the present framework: (i) network analysis, enabling graph-based computation of route redundancy and alternative-path availability; (ii) spatial overlay operations, allowing heterogeneous data layers (road hierarchy, building density) to be aggregated over a common grid; and (iii) grid-based spatial discretization, ensuring that indicators are comparable and transferable across different urban contexts. Despite their potential, these methods have seldom been applied to characterize last-mile delivery resilience for modular construction, particularly through indicators explicitly accounting for road-network structure and redundancy.

As a result, a methodological gap persists at the intersection of modular construction, last-mile logistics, and urban system resilience: spatially explicit and network-informed frameworks capable of assessing last-mile delivery resilience using interpretable and transferable indicators remain limited. To address this gap, this paper proposes a GIS-based, network-informed multi-criteria framework integrating three complementary dimensions: road access suitability, truck-feasible network redundancy, and urban morphology operability. Indicators are computed over a regular spatial grid to enable comparability and transferability across urban contexts. The city of Lille (France) is used as a pilot case representative of dense European urban environments with pronounced last-mile constraints for construction logistics.

The remainder of the paper is organized as follows. Section 2 reviews relevant literature. Section 3 presents the methodology and data sources. Section 4 reports the results for the Lille case study, Section 5 discusses the findings and recommendations, and Section 6 concludes and outlines future research perspectives.

2 State of the Art

This section reviews prior research at three nested levels: (i) supply-chain resilience in construction and modular/prefabricated delivery systems, (ii) last-mile logistics and construction logistics constraints in dense urban environments, and (iii) spatially explicit assessment methods (GIS-based indicators and multi-criteria approaches) enabled by open geospatial data. The review follows a funnel logic from general concepts to the specific gap addressed by this paper.

2.1 Supply-chain resilience in construction and modular systems

Supply-chain resilience is commonly defined as the capability of a supply network to anticipate, absorb, adapt to, and recover from disruptions while maintaining essential functions. In construction, resilience discussions have intensified due to increasingly complex procurement structures, fragmented stakeholders, and exposure to shocks (supply shortages, transport disturbances, regulatory changes). Recent synthesis works highlight that disruption research remains fragmented and that resilience operationalization often lacks consistent and measurable indicators comparable across contexts [8, 9].

Modular and prefabricated construction systems strengthen the coupling between manufacturing, transportation, and on-site assembly, thereby increasing sensitivity to delivery reliability and urban access constraints. Quantitative and conceptual contributions have addressed modular logistics through optimization models, buffering and sourcing strategies, and conceptual frameworks. For instance, two-stage stochastic programming has been used to optimize modular logistics decisions across manufacturing–inventory–transportation under demand variability, illustrating the value of mathematical decision-support primarily at the project planning level rather than at an urban last-mile territorial scale [10]. Systematic works further emphasize disruption drivers (including transportation and procurement as critical levers) and resilience mechanisms (e.g., redundancy, flexibility, collaboration, digitalization), yet rarely translate these concepts into spatially explicit indicators supporting local last-mile deployment [1, 2, 5].

2.2 Last-mile logistics and construction logistics in dense cities

Last-mile logistics is widely characterized as the most complex and least efficient segment of urban supply chains due to high uncertainty, limited space, conflicts with other urban functions, and dynamic regulatory constraints. Literature reviews highlight recurring barriers such as congestion, limited curb space, access restrictions, and the need to balance economic, environmental, and social performance [3]. Cities nevertheless often under-integrate last-mile logistics into planning despite its growing impact, calling for locally adapted operational and regulatory instruments [11].

Construction logistics intersects with city logistics but exhibits distinct characteristics: heavy and oversized deliveries, temporal criticality aligned with installation windows, safety constraints, and site-interface limitations. Empirical studies on construction logistics centers (CLCs) show that logistics strategies (consolidation vs. just-in-time deliveries) significantly influence delivery patterns and disturbances, while implementation barriers remain substantial [4, 12]. Despite these advances, most last-mile research still focuses on retail and e-commerce flows, whereas construction logistics studies often remain project-centric. Modular construction, whose installation is delivery-dependent and schedule-critical, therefore requires last-mile analysis that is both urban-system oriented and operationally grounded.

2.3 Spatially explicit assessment and GIS-based multi-criteria approaches

Supply-chain resilience and accessibility challenges in dense urban contexts are increasingly addressed through GIS-based indicators and multi-criteria decision analysis (MCDA), enabling heterogeneous data layers (transport, morphology, constraints) to be integrated into comparable territorial scores [6, 7]. In parallel, network science provides measures (e.g., redundancy, alternative routing potential) to describe transport network robustness under disruption. However, in construction logistics, and particularly in modular last-mile delivery, these approaches are still rarely instantiated as reproducible indicator sets supporting urban zoning and actionable recommendations. Data availability constitutes a practical challenge: OSM, widely used for road-network extraction, reaches sufficient quality for urban analytical uses when limitations are explicitly acknowledged, though quality varies by geography and feature type [13, 14].

2.4 Synthesis of gaps and positioning of this paper

Three gaps emerge: modular supply-chain studies rarely operationalize last-mile constraints spatially [2, 5]; urban last-mile research targets retail flows rather than construction [3, 11]; and GIS-MCDA frameworks lack a bridge to modular last-mile resilience metrics.

3 Methodology and Data

A spatially explicit, network-informed multi-criteria framework was developed to assess urban last-mile delivery resilience for modular construction. The framework integrated (i) road access suitability, (ii) truck-feasible network redundancy, and (iii) urban morphology operability into normalized indicators computed over a regular grid. The approach followed established principles from GIS-based multi-criteria analysis and urban freight/logistics assessment, while explicitly operationalizing network redundancy as a resilience property [3, 7, 4].

3.1 Study area and spatial discretization

The city of Lille (France) was selected as a pilot case representative of dense European urban conditions where modular construction deliveries face significant last-mile constraints. The study area was defined as a polygonal extent within which all computations were performed.

The area was discretized into a regular grid of square cells of side length $\Delta = 250$ m. Let $\mathcal{G} = \{g_1, \ldots, g_N\}$ denote the set of grid cells, with $A_g = \Delta^2$ the area of a cell. A grid-based formulation was adopted to ensure spatial comparability and transferability across cities, as commonly required for spatial decision-support and multi-criteria mapping [7].

3.2 Open data sources and preprocessing

OpenStreetMap (OSM) data were used for road and building layers to ensure transparency and reproducibility, while explicitly acknowledging quality and fitness-for-use limitations [14, 13].

Road geometries and attributes (including the `highway` classification) were extracted and clipped to the study boundary. Building footprints were extracted using OSM `building` tags and filtered to retain polygonal geometries. All layers were re-projected to a metric coordinate reference system (Lambert-93 EPSG:2154) to enable consistent length and area computations.

3.3 Road-network representation and truck-feasible subnetwork

The road network was represented as a graph $\mathcal{N} = (V, E)$, where V denotes intersections and E road segments. Each edge $e \in E$ had a geometric length L_e and an OSM road class $h(e)$.

Truck feasibility was operationally defined based on OSM road classes by excluding residential, service, and pedestrian roads, consistent with typical heavy and oversized vehicle constraints in urban construction logistics. This filtering approximates the access constraints applicable to the standard semi-trailer configuration used for modular deliveries in France: total length 16–18 m, width 2.5 m, maximum authorized gross weight 44 tonnes. Such vehicles are structurally incompatible with residential and service roads due to geometric (turning radius, lane width) and load-bearing constraints. Vertical clearance restrictions (e.g., overpasses, underpasses) were not modeled at this stage, as OSM does not systematically provide `maxheight` attributes across the study area; this constitutes an explicitly acknowledged limitation (Section 6).

A truck-feasible subnetwork $\mathcal{N}_T = (V_T, E_T)$ was derived by retaining edges satisfying a feasibility rule $\phi(e) = 1$ based on road class and intended modular delivery constraints. This subnetwork enabled redundancy analysis under truck-feasible conditions, which is central to resilience assessment [2, 5].

3.4 Indicator definition and mathematical formulation

Three criteria were computed per grid cell $g \in \mathcal{G}$ and normalized to $[0, 1]$ for comparability. Their selection was grounded in the specific constraints of modular last-mile delivery. C1 (road access suitability) captures the physical compatibility of the road environment with oversized vehicles—the necessary entry condition for any modular delivery. C2 (truck-feasible network redundancy) directly operationalizes resilience as the availability of alternative routing options under disruption, which is the defining structural vulnerability of modular logistics in dense urban networks. C3 (urban morphology operability) captures site-interface constraints related to building density, conditioning on-site maneuvering and staging capacity. Other potential factors—including real-time traffic, time-window regulations, and low-emission zones—were excluded because they require dynamic or proprietary data unavailable across cities; their influence is partially captured through road hierarchy classification and acknowledged in Section 6.

3.4.1 C1: road access suitability

C1 quantified the suitability of the local road environment for modular deliveries using road hierarchy as a proxy for capacity and maneuverability. Each road segment e intersecting grid cell g was assigned a suitability score $s(h(e)) \in [0,1]$ based on its road class $h(e)$. Let E_g denote the set of edges intersecting g and $L_{e,g}$ the length of edge e within g.

The raw suitability score was defined as the length-weighted mean:

$$C1^{raw}(g) = \frac{\sum_{e \in E_g} s(h(e))\, L_{e,g}}{\sum_{e \in E_g} L_{e,g} + \varepsilon}, \qquad (1)$$

where $\varepsilon > 0$ avoided division by zero. This formulation ensured proportional contribution of longer segments and boundedness in $[0,1]$ prior to normalization.

3.4.2 C2: truck-feasible network redundancy

C2 operationalized local redundancy of the truck-feasible network as a resilience property using two complementary proxies: (i) truck-feasible edge-length density and (ii) branching opportunity density [8].

Let $E_{T,g}$ denote the set of truck-feasible edges intersecting cell g and define the edge-length density:

$$\rho_L(g) = \frac{\sum_{e \in E_{T,g}} L_{e,g}}{A_g}. \qquad (2)$$

Let $V_{T,g}$ be the set of truck-feasible nodes within g, with degree $\deg_T(v)$ in $\mathcal{N}_T$. Define the branching node set $B_g = \{v \in V_{T,g} : \deg_T(v) \geq 3\}$ and branching density:

$$\rho_B(g) = \frac{|B_g|}{A_g}. \qquad (3)$$

The raw redundancy score was computed as:

$$C2^{raw}(g) = \left(\frac{\rho_L(g)}{\max_{g' \in \mathcal{G}} \rho_L(g') + \varepsilon}\right)\left(\frac{\rho_B(g)}{\max_{g' \in \mathcal{G}} \rho_B(g') + \varepsilon}\right), \qquad (4)$$

yielding high values only where sufficient truck-feasible infrastructure and multiple branching opportunities coexist.

3.4.3 C3: urban morphology operability

C3 characterized urban operability using building footprint density as a proxy for spatial constraints. Let $\mathcal{P}_g$ denote the set of building polygons intersecting grid cell g, and $A_{p,g}$ the area of polygon p within g. The built-up ratio was defined as:

$$\beta(g) = \frac{\sum_{p \in \mathcal{P}_g} A_{p,g}}{A_g}. \qquad (5)$$

Higher built-up ratios implied tighter spatial conditions; operability was therefore defined via inversion and normalization (see Section 3.5).

3.5 Normalization and direction harmonization

All criteria were mapped to a common scale $[0,1]$ using min–max normalization:

$$\mathcal{N}(x(g)) = \frac{x(g) - \min_{g' \in \mathcal{G}} x(g')}{\max_{g' \in \mathcal{G}} x(g') - \min_{g' \in \mathcal{G}} x(g') + \varepsilon}. \qquad (6)$$

Final normalized indicators were defined as:

$$C1(g) = \mathcal{N}(C1^{raw}(g)), \qquad (7)$$

$$C2(g) = \mathcal{N}(C2^{raw}(g)), \qquad (8)$$

$$C3(g) = 1 - \mathcal{N}(\beta(g)). \qquad (9)$$

Higher values therefore always corresponded to more favorable conditions for modular last-mile delivery resilience.

3.6 Linking the three criteria for zoning and decision support

To support interpretable zoning while avoiding black-box indices, a transparent composite score was optionally defined:

$$R(g) = w_1\, C1(g) + w_2\, C2(g) + w_3\, C3(g), \quad \sum_{i=1}^{3} w_i = 1,\ w_i \geq 0. \qquad (10)$$

A baseline equal-weight configuration $w_1 = w_2 = w_3 = \frac{1}{3}$ was adopted as the epistemically neutral prior: in the absence of empirical weighting evidence (e.g., expert survey data or revealed logistics preferences for the Lille context), equal weights avoid introducing arbitrary priorities that cannot be validated against field data at this pilot stage. A sensitivity check varying each w_i within [0.10, 0.60] confirmed that the spatial ranking of the most critical zones remained stable under all tested configurations [7].

3.7 Implementation and replicability

All steps (data extraction, preprocessing, spatial overlays, indicator computation, normalization, and visualization) were implemented in Python using open-source geospatial and network libraries. The workflow was fully scripted to ensure reproducibility given the same boundary definition, grid resolution, and OSM data snapshot.

4 Results

This section presents the results of the spatial multi-criteria analysis applied to the city of Lille. Results are reported separately for each criterion in order to distinguish the respective effects of road access suitability, truck-feasible network redundancy, and urban morphology operability on last-mile delivery resilience for modular construction. Both spatial patterns and statistical distributions are presented.

4.1 Road access suitability (C1)

Criterion C1 quantified the physical suitability of the local road network for modular construction deliveries based on road hierarchy and length distribution. Figure 1 shows the spatial distribution of C1 values across the 250 m grid covering the study area.

The results revealed a strong spatial heterogeneity in road access suitability. Grid cells located along major urban corridors and near primary road infrastructures exhibited high C1 values, indicating favorable access conditions for heavy and oversized vehicles. In contrast, dense residential areas characterized by a predominance of local and service roads were associated with low C1 values.

From a statistical perspective, the distribution of C1 values was highly asymmetric, with a large proportion of grid cells exhibiting very low access suitability. The median C1 value was equal to zero, reflecting the structural predominance of constrained road segments in the urban fabric. High C1 values were limited to a small number of grid cells, mainly aligned with major transport axes.

4.2 Truck-feasible network redundancy (C2)

Criterion C2 assessed the redundancy of the truck-feasible road network by evaluating the availability of alternative routes and branching opportunities within each grid cell. The spatial distribution of C2 values is presented in Figure 2.

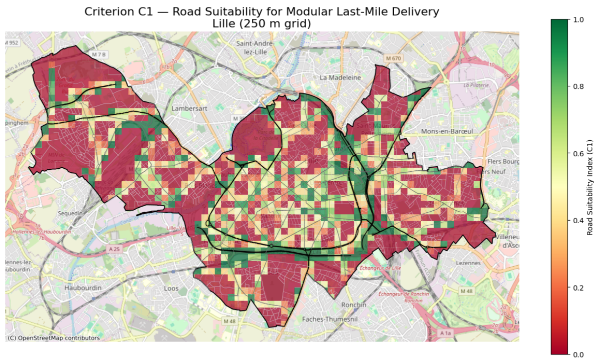

Figure 1. Spatial distribution of road access suitability (C1) for modular construction last-mile delivery in Lille (250 m grid). Normalized scale 0–1: $C1 < 0.2$ (red) indicates low suitability (predominantly residential and service roads); $C1 > 0.8$ (green) indicates high suitability (primary arterial corridors); intermediate values reflect mixed road-class environments.

The results showed that network redundancy was extremely limited across most of the study area. A very large majority of grid cells exhibited C2 values close to zero, indicating the absence of locally available alternative truck-compatible routes. Higher C2 values were observed only in a small number of locations, generally near major intersections and high-capacity road segments.

The statistical distribution of C2 values was strongly skewed toward zero, with a mean value close to zero and very limited dispersion. This pattern is also structurally expected from the multiplicative formulation of C2 (Eq. 4): high values require both truck-feasible edge-length density and branching node density to be simultaneously non-negligible within the same cell, a condition that is intrinsically rare in a dense urban network where the truck-feasible subnetwork is sparse by construction. This distribution highlighted a structurally fragile last-mile network configuration, in which physical access did not necessarily imply resilience to disruptions such as road works, congestion, or temporary access restrictions.

4.3 Urban morphology operability (C3)

Criterion C3 evaluated the operability of the urban morphology by analyzing building density and footprint concentration as proxies for on-site spatial constraints. Figure 3 presents the spatial distribution of C3 values over the study area.

The results indicated generally high C3 values across the majority of grid cells, reflecting favorable urban morphology conditions for last-mile construction operations.

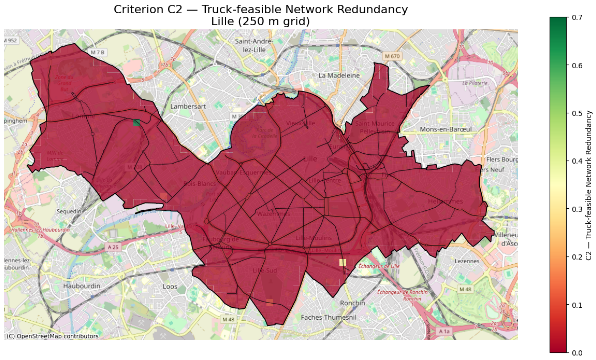

Figure 2. Spatial distribution of truck-feasible network redundancy (C2) in the Lille last-mile context. Normalized scale 0–1: $C2 < 0.2$ (dark red) indicates no or negligible locally available alternative truck-compatible routes; $C2 > 0.8$ indicates high redundancy, observed only near major high-capacity intersections. The near-zero distribution reflects both the structural scarcity of truck-feasible routes from road-hierarchy filtering (Section 3.3) and the multiplicative formulation of C2, which requires simultaneous non-negligible edge density and branching density (Section 3.4.2).

Lower C3 values were mainly concentrated in areas characterized by high building density and compact urban forms.

The statistical distribution of C3 values showed a concentration toward high operability levels, with a high mean value and limited dispersion. This pattern suggested that, at the city scale, urban morphology imposed fewer constraints on modular construction last-mile operations than road access and network structure.

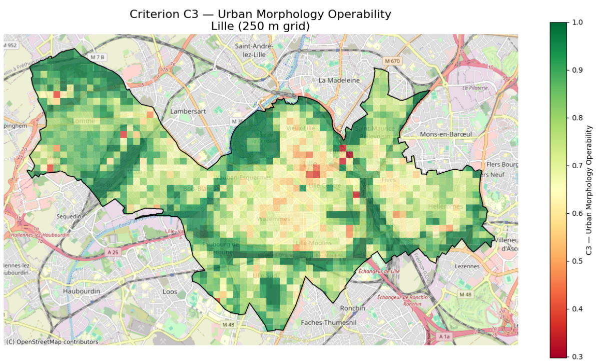

Figure 3. Spatial distribution of urban morphology operability (C3) in the Lille study area. Normalized scale 0–1: $C3 < 0.2$ indicates low operability (dense, compact built-up areas with high building footprint coverage); $C3 > 0.8$ indicates high operability (sparse or open urban fabric with low building coverage).

4.4 Statistical distribution of resilience indicators

Figure 4 presents the statistical distributions of the three normalized criteria (C1, C2, and C3) computed over the 250 m grid covering the city of Lille. The distributions highlight strong contrasts between access suitability, network redundancy, and urban morphology operability in the last-mile delivery context.

C1 showed a highly asymmetric distribution with a median of zero, confirming the structural predominance of constrained roads, while approximately 25% of cells exceeded moderate suitability along major corridors. C2 was strongly skewed toward zero, more than 90% of cells exhibited near-zero redundancy, revealing a structurally fragile network where most locations depend on a single truck-compatible route. C3 concentrated toward high values (median > 0.80), indicating that urban morphology imposed fewer constraints than network structure. Together, these distributions confirm that last-mile resilience in Lille is primarily limited by network-related factors.

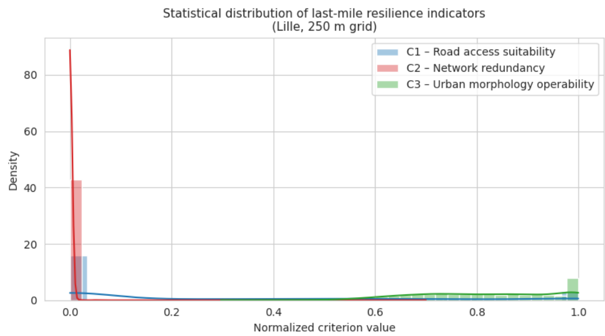

Figure 4. Statistical distributions of road access suitability (C1), truck-feasible network redundancy (C2), and urban morphology operability (C3) across the Lille study area (250 m grid, kernel density estimates).

5 Discussion and Recommendations

5.1 Network structure as the primary driver of last-mile resilience

The results demonstrated that last-mile delivery resilience for modular construction in Lille was primarily governed by road network structure rather than by local accessibility alone. Although road access suitability (C1) exhibited marked spatial heterogeneity, truck-feasible network redundancy (C2) remained extremely low across the majority of the study area. This interpretation is directly supported by the near-zero median values of C2 and its very limited dispersion (Figure 4), in contrast with the extended upper tail observed for C1 along major corridors.

The near-zero values observed for C2 in most grid cells reflected a structural dependence on a limited number of truck-compatible routes. Such configurations increased sensitivity to localized disruptions, including road works, congestion, and temporary access restrictions. This vulnerability is consistent with the spatial pattern of C2 (Figure 2), where higher redundancy is confined to a small number of cells near major intersections and high-capacity segments. These findings are consistent with resilience theory in urban systems, which emphasizes redundancy and alternative paths as key properties for disturbance absorption and recovery. In dense European urban contexts, historical road hierarchies and planning priorities have often concentrated freight traffic on a small number of corridors, thereby limiting redundancy at the local scale.

5.2 Limited influence of urban morphology in dense last-mile contexts

Urban morphology operability (C3) exhibited generally high values across the study area, with limited dispersion compared to access- and network-related criteria. This result is directly supported by the concentration of C3 toward high values (median exceeding 0.80 in Figure 4) and by the spatial distribution in Figure 3, where low operability is limited to compact and highly built-up areas. These patterns suggested that spatial constraints related to building density and footprint concentration were not the dominant limiting factors for last-mile modular construction operations in Lille.

This finding can be explained by the fact that conventional construction practices already operate under constrained urban conditions, relying on regulated temporary occupation of public space, staged deliveries, and adaptive on-site logistics. As a result, morphology-related constraints can often be operationally mitigated at the site interface, whereas limitations imposed by road network structure are more difficult to compensate. The results therefore indicated that, in dense urban environments, improving last-mile resilience requires a stronger focus on network-level characteristics rather than solely on site-scale spatial availability.

5.3 Distinguishing accessibility from resilience in modular construction logistics

A key outcome is the distinction between accessibility (C1, nominal conditions) and resilience (C2, functionality under disruption). The divergence between these criteria—heterogeneous C1 versus near-zero C2 in over 90% of cells—shows that accessibility alone is insufficient as a resilience indicator (Figure 4). For modular construction, where alternative routes are non-negotiable given dimensional constraints, the framework formalizes this distinction spatially, addressing a gap in existing supply-chain resilience studies.

5.4 Operational, territorial, and regulatory recommendations

Based on the identified spatial patterns, several recommendations can be derived. At the operational level, delivery planning for modular construction should explicitly account for local network redundancy, rather than relying solely on shortest-path or nominal access criteria. In practice, low-C2 areas (Figures 2 and 4) should be treated as disruption-sensitive zones where contingency routing, time-buffering, and coordination with on-site installation windows become critical. Identifying critical corridors and intersections can support more robust routing strategies and contingency planning.

At the territorial level, targeted interventions on the few high-C2 links and junctions may yield significant resilience improvements without extensive network modifications. At the regulatory level, urban access policies and temporary road occupation permits could be adapted to reflect network resilience considerations. Coordinated scheduling of road works and construction activities along critical corridors may reduce cumulative disruption effects, particularly in contexts where redundancy is structurally low (C2 near zero across most cells). More broadly, integrating last-mile resilience diagnostics into urban planning and construction permitting processes could support the deployment of modular construction systems in dense cities.

6 Conclusion

This paper proposed a GIS-based, network-informed multi-criteria framework to assess last-mile delivery resilience for modular construction in dense urban environments, integrating three complementary indicators: road access suitability (C1), truck-feasible network redundancy (C2), and urban morphology operability (C3), demonstrated on the city of Lille.

The results revealed that favorable access for modular deliveries was concentrated along a limited number of major corridors (C1), while truck-feasible network redundancy (C2) emerged as the most critical limiting factor, with near-zero values across most of the study area. Urban morphology operability (C3) remained comparatively favorable. These findings emphasize that accessibility alone does not guarantee last-mile resilience, and that road network redundancy plays a decisive role for modular construction logistics.

Several limitations must be acknowledged: reliance on open geospatial data with possible local inaccuracies; road-class filtering without explicit modeling of vertical clearance or axle load restrictions (reference configuration: semi-trailer, 16–18 m, 44 t); exclusion of regulatory constraints such as time windows and low-emission zones; and a static spatial scope that does not capture temporal variability.

Future research should incorporate regulatory and temporal dimensions, empirical validation using real logistics data, vehicle-specific network filtering, and application to other urban contexts to support transferable guidelines for modular construction last-mile resilience.

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