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# Decarbonising construction logistics: the role of supplier-led distribution and integrated warehousing

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## Abstract

**Purpose** – This study aims to examine how supplier-led distribution and integrated warehousing enhance transport efficiency and reduce embodied carbon in construction logistics. Focusing on plasterboard delivery in Auckland's linear urban context, it examines how early supplier engagement and forward-stocking can reconfigure logistics operations to address spatial and operational challenges, decarbonising the construction supply chain.

**Design/methodology/approach** – This case-based analysis uses empirical data from supplier-managed plasterboard distribution in Auckland to assess how logistics reconfiguration – supplier-led deliveries and integrated warehousing – impacts transport efficiency and carbon embodiment. Carbon outcomes are quantified using Environmental Product Declarations and New Zealand freight emissions benchmarks, with application of spatial analysis and supply chain modelling to evaluate the impacts of forward-stocking and supplier engagement on fragmented construction logistics.

**Findings** – The study finds that supplier-led distribution, integrated warehousing and forward-stocking significantly enhance transport efficiency by consolidating deliveries and reducing vehicle movements, resulting in measurable embodied carbon reductions. It underscores the importance of early supplier engagement and spatially responsive logistics planning in addressing urban sprawl, demonstrating that reconfigured supply chains offer both operational and environmental benefits towards construction sector decarbonisation.

**Originality/value** – The paper analyses the interplay of distribution, transport and warehousing in linear sprawl, proposing an integrated transport-driven warehousing model. It demonstrates improved efficiency through supplier-centric distribution and challenges status-quo transport life cycle assessment, typically overlooked due to data availability constraints. Theoretically, it extends employment of operations research, limited to manufacturing and freight transport, in construction as a defragmentation enabler. It also argues for municipalities to require logistics plans, to bridge policy-practice gaps.

**Keywords** Construction decarbonisation, Construction transport, Embodied carbon, Integrated warehousing, Logistics sprawl, Urban distribution

**Paper type** Research paper

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## Abbreviations

2PL = second party logistics;
BAU = business as usual;
BM = builders' merchant;
CG = centre of gravity;
DC = distribution centre;
DTS = direct to site;
EPD = environmental product declaration;
FIS = freight into store;
FTL = full truck load;
GVM = gross vehicle mass;
GWP = global warming potential;
ID = identifier;
IRP = inventory routeing problem;
JIT = just in time;
kg $CO_2$-e = kilograms of carbon dioxide equivalent;
L/day = litres (of fuel) per day;
L/trip = litres (of fuel) per truck trip;
LCA = life cycle assessment;
LP = linear programming;
MAE = mean absolute error;
MAPE = mean absolute percentage error;
MSE = mean squared error;
Q-Q = quantile-quantile;
$R^2$ = co-efficient of determination;
RMSE = root mean squared error;
SMAPE = symmetric mean absolute percentage error;
SPSS = statistical package for social sciences (software);
VMI = vendor managed inventory; and
VRP = vehicle routeing problem.

## 1. Introduction

Construction is an engineer-to-order industry producing unique artefacts at fixed locations with temporary project organisations and fragmented supply chains built on short-term collaborations (Badarudin *et al.*, 2024; Cigolini *et al.*, 2022). Multiple parties form temporary networks to coordinate production (Karrbom Gustavsson and Hallin, 2015). Complexity from this fragmentation, compounded by siloed operations and sequential workflows (Riazi *et al.*, 2020), results in poor coordination, communication and integration (Lafhaj *et al.*, 2024). The consequent "chain of problems" undermines delivery performance (Bäckstrand and Fredriksson, 2022). The on-site/off-site interface further suffers from ambiguous responsibilities, lack of standardised procedures and inadequate management tools (Tetik *et al.*, 2021).

The need for time-critical resource deliveries on fixed yet temporary urban construction sites creates inherent logistical dependencies (Tetik *et al.*, 2025; Dixit *et al.*, 2022). Construction logistics operates at two levels: on-site activities and external resource flows (Ruzieh *et al.*, 2025). The fragmented supply chain and bespoke procurement necessitate integrated on- and off-site management with clearly defined responsibilities (Cigolini *et al.*, 2022; Vrijhoef and Koskela, 2000). Planning plays a central role in operational alignment by extending coordination and decision-making beyond the focal organisation (Love *et al.*, 2004; Tavo and Rasmus, 2024; Jonsson and Holmström, 2016). Integrated planning requires cooperation (long-term relationships, trust and shared risk/reward), coordination (shared goals, customer focus and information sharing) and integration (behaviours and processes). Despite its centrality, logistics planning remains underdeveloped in construction (Bäckstrand and Fredriksson, 2022). The recent growth of interest in construction logistics – distinct from freight logistics – stems from its wider scope, complex stakeholder network, managerial challenges and sustainability implications (Fredriksson *et al.*, 2020; Fredriksson and Huge-Brodin, 2022; Fredriksson *et al.*, 2024a; Fredriksson *et al.*, 2025a; Haag and Jünger, 2023; Janné and Fredriksson, 2022; Dhawan *et al.*, 2023a; Sezer and Fredriksson, 2021).

Transport constitutes a major and critical element of construction logistics (Tetik *et al.*, 2025; Bowersox *et al.*, 2020). Construction deliveries require diverse, time-sensitive trips for bulk material, structural components, excavated soil, infill, finishing materials and operational supplies (Vrijhoef, 2020; Brusselaers *et al.*, 2025). The related transport movement contributes to road congestion, disrupting the synchronisation between production and delivery, thereby decreasing productivity (Tetik *et al.*, 2025; Thunberg and Fredriksson, 2018). On-site spatial constraints exacerbate risks from poorly timed deliveries (Tetik *et al.*, 2021) leading to material damage (Hasselsteen *et al.*, 2024; Tsegay *et al.*, 2023). Loading/unloading delays impair both on- and off-site productivity (Naz and Fredriksson, 2023). Reducing on-site delays enhances contractor and transporter efficiency (Sezer and Fredriksson, 2021), while minimising off-site delays enhances overall transport performance (Naz *et al.*, 2022). Recent studies for mitigating transport-related inefficiencies include resource and asset sharing by Tan *et al.* (2023) integrated distribution models by Hosseinzadeh Moghaddam *et al.* (2025) and decision-support optimisation frameworks by Timperio *et al.* (2020) However, their sector-generic context overlooks construction-specific complexities – fragmented supply chains, temporary and customised logistics setups and embodied carbon assessment. Increasing attention on wider societal impacts of construction transport is evidenced from studies by Haag and Jünger (2023), Rönnberg *et al.* (2023) and Fredriksson *et al.* (2025b).

Suppliers play a key role in transport efficiency and delivery performance through mode selection, routeing and service design (Naz, 2022; Santén and Rogerson, 2018). However, construction logistics remains largely contractor-centric, being traditionally regarded as an operational function (Eriksson and Fredriksson, 2025). This limits supplier participation for effective delivery planning (Bäckstrand and Fredriksson, 2022). Though, when operationalised, supplier-led deliveries tend to enhance transport efficiency through higher load consolidation, improved capacity utilisation and reduced vehicle movements (Arvidsson *et al.*, 2013; Naz, 2024), concurrently, reducing external costs (Schröder *et al.*, 2023). Addressing this issue, however, requires customised logistics/transport model development (Abideen *et al.*, 2023). Advanced supply chain analytics offer transformative potential through informed decision-making, refined delivery scheduling and process optimisation (Pundir *et al.*, 2024). Operational data analysis, therefore, has the capability to streamline processes, reduce redundancies and align with decarbonisation goals. However, current limitations – limited availability of comprehensive data and its trip-centricity rather than supply chain focus – constrain evidence-based distribution modelling (McKinnon, 2015; Dhawan *et al.*, 2024a).

This study investigates how the shift from intermediary-based distribution to direct manufacturer-to-site delivery affects transport efficiency and informs improved warehousing strategies for intermediate stocks. It further examines the impact of distribution design on transport activity and supply chain configuration. As logistics networks extend into urban sprawl, adaptive transport models become critical. The research problem seeks to develop evidence-based insights for synthesising optimal supply chain structures and adaptive transportation frameworks with carbon reduction as a core performance metric. The analysis examines supplier-led plasterboard distribution in Auckland, New Zealand, optimised using operations research tools. A comparison of business-as-usual (BAU) and reconfigured supply chains validates the potential for cleaner distribution. The reconfigured supply chain adopts "integrated warehousing" that decentralises manufacturer stocks to regional locations closer to demand centres, improving transport efficiency and facilitating flexible warehousing aligned with urban development patterns. The specific research questions investigated are:

*RQ1*. How does transport optimisation impact supply chain configuration, specifically warehousing?

*RQ2*. What is the impact of the optimised transport and the modified supply chain configuration on transport-related carbon emissions?

This paper contributes to the significance of transport emissions for sustainability of the built environment from the life cycle assessment (LCA) perspective. LCA is a standardised method for evaluating environmental impacts across a product's life cycle. European standard EN 15978 outlines the LCA information components across a building's life cycle: product, construction, use and end-of-life stages, with an optional beyond life cycle stage. The product stage covers material supply (A1), transport (A2) and manufacturing (A3); construction includes delivery (A4) and installation (A5); use addresses maintenance, replacement and operational energy or water use (B1–B7); and end-of-life involves demolition, waste handling and disposal (C1–C4). Stage D captures potential benefits from reuse, recycling and energy recovery beyond the life cycle (Sturgis *et al.*, 2023). LCA facilitates comparison of materials, components, services and entire buildings based on environmental parameters (Szalay *et al.*, 2022).

Carbon gets embodied throughout all stages of a building's life cycle due to resource use (Lützkendorf and Balouktsi, 2022), though reduction efforts focus mainly on production (A1–A3) (US DoE, 2024). Transport emissions (A4), despite their significance, are often overlooked due to inconsistent operational data and high assessment costs (Naz, 2022). Our study addresses this gap through a data-driven analysis of operational transport carbon, examining its influence on supply chain configuration and contribution to built environment decarbonisation. Its novelty lies in integrating real-world data, case study analysis and quantitative modelling – advancing beyond the predominantly qualitative focus of earlier studies (Ruzieh *et al.*, 2025; Fredriksson *et al.*, 2024b).

The remainder of the paper is structured as follows: Section 2 – literature review contextualising relevant issues; Section 3 – data acquisition and validation; Section 4 – data analysis, carbon impacts and synthesis of integrated warehousing strategy; Section 5 – discussion and managerial/theoretical contributions; and Section 6 – conclusion including achievements, limitations and future work.

## 2. Theoretical background and literature review

Urban sprawl disrupts construction logistics by decentralising construction activity, thereby extending transport distances (Galiano *et al.*, 2021; Trent and Joubert, 2022). This undermines the efficiency of hub-and-spoke models (Xu *et al.*, 2021). Since the mid-1800s, Auckland has evolved into a polycentric conurbation with linear growth along transport corridors and coastlines (Silva, 2018; Hoffman, 2019; Xu and Gao, 2021). Persistent outward expansion disperses development from the urban core (Silva, 2018; Richardson, 2022), increasing transport movements between established (freight generating) and developing (freight attracting) areas, exacerbating logistics problems (Trent and Joubert, 2022; Gardrat, 2021). Higher trip frequency, smaller deliveries and lower load factors increase per-unit emissions (Mohapatra *et al.*, 2021). Supply chains respond to "logistics sprawl" by relocating warehouses and expanding logistics activities towards urban peripheries, driven by limited land availability within the urban core and the logistical imperative to service outward development (Dablanc, 2007). Logistics sprawl increases vehicle-kilometres-travelled due to increased haul distances (Mohapatra *et al.*, 2021), however, its impact on reduction of transport activity is not substantiated in the literature (Trent and Joubert, 2022; Heitz *et al.*, 2017; Kang, 2020a; Kang, 2020b; Sakai *et al.*, 2018). Despite their interdependence, urban sprawl and freight transport are often examined separately (Gardrat, 2021; Feng and Gauthier, 2019).

Supplier-led distribution is one of the strategies to manage transport activity in response to urban sprawl (Dhawan *et al.*, 2024a; Vidalakis and Tookey, 2005). This approach facilitates capacity-sharing arrangements (Melo *et al.*, 2019) by placing "floating stock" (unallocated material pushed into the supply chain by the manufacturer) (Dekker *et al.*, 2009) in consumption-proximal warehouses (Skipper *et al.*, 2010). This can feed back into transportation activity reduction (e.g. reduced empty running) (Pourakbar *et al.*, 2009). However, empirical evidence validating logistics sprawl-based reduction in transport activity is an identified research gap (Trent and Joubert, 2022; Kang, 2020a; Kang, 2020b; Sakai *et al.*, 2017). Our study addresses this gap by integrating spatial analysis with transport efficiency modelling to develop sustainable distribution strategies (Lyu *et al.*, 2025). It further quantifies the resultant reduction in embodied carbon (Simonen *et al.*, 2019; Xiang *et al.*, 2023), overcoming an existing methodological gap (Naz, 2022).

The literature review addresses key themes that establish the relationship between construction logistics and urban sprawl, focussing on the distribution of manufactured construction products and freight transport efficiency.

### *2.1 Manufactured construction products distribution*

Optimal distribution network design, that balances service levels and costs, is an essential component of supply chain delivery efficiency. Strategic location of supply chain elements, specifically warehouses, facilitates consolidation and redirection of goods, regulation of fleet size and its composition, and transport optimisation considering variables like distance, load size and product type (Rodríguez *et al.*, 2022). Modelling such systems enables addressing complex network design challenges. In context, the inventory routeing problem (IRP) extends the vehicle routeing problem (VRP) by including inventory costs, integrating logistics and inventory management to minimise transport and handling costs while optimising capacity utilisation. It is closely linked to vendor managed inventory (VMI), where suppliers optimise delivery timing, quantities and routeing based on customer inventory requirements, generating mutual cost and efficiency benefits (Harahap *et al.*, 2024).

Distribution systems may be structured either as centralised, where manufacturers deliver directly to consumption points, or decentralised, where bulk stocks are transferred to regional depots or distribution centres (DCs) for local distribution (Milewski, 2020). Centralised systems consolidate inventory and decision-making at a single location, achieving economies of scale and streamlined operations. Aggregation of uncertainty across all demand points reduces supply chain inventory levels, at the same time limiting responsiveness and flexibility in dynamic environments. Decentralised systems, by contrast, distribute inventory across multiple DCs, enhancing flexibility and responsiveness, however, increasing inventory and carrying costs due to dispersed service requirements (Cantini *et al.*, 2021; Cantini *et al.*, 2022; Cantini *et al.*, 2025). In the transport context, a centralised system increases distribution tonne-km, while tending to reduce the overall transportation activity, and therefore, associated costs and emissions due to the higher service level from "risk-pooling" (Milewski, 2020; Trigos and Doria, 2025; Kohn and Brodin, 2008).

A common distribution system configuration is the three-tier setup (factory–depot–customer) (Holzapfel *et al.*, 2023), with depot networks shaped by product attributes, service demands, delivery volumes and marketing strategies (Lim and Srai, 2015). Effective system design involves optimising number of depots, their location and capacity; managing inventory; selecting cost-efficient transport modes; and coordinating service strategies through third-party logistics using contracted/in-house transport fleet (McKibbin, 1976). The manufactured construction products distribution chain, a three-tier configuration, has bulk suppliers and construction sites at either end, with intermediaries (builders' merchants [BMs] and retailers) interposed between them. These elements, individually comprising delineated supply chains/networks, are linked together by an external transport supplier into a loosely connected network (Dubois and Gadde, 2002; Sandberg *et al.*, 2021) centred around individual deliveries. In the context of this study, distribution is vertically integrated with manufacturing, creating a bespoke, supplier-driven model that reflects the servitisation of manufacturing through downstream vertical integration (Kamal *et al.*, 2020; Yao *et al.*, 2024).

Intermediaries provide storage and material consolidation (van Hoek, 2000; Mandal and Jain, 2023), though storage is associated with each tier of the distribution chain (manufacturer/bulk supplier – bulk stocks; intermediaries – buffer stocks; site – materials awaiting use). Two primary distribution methods exist: direct-to-site (DTS) and freight-into-store (FIS). DTS involves direct delivery of large consignments (e.g. steel framing) to the site, bypassing intermediaries, while FIS – more commonly used – channels retail quantities through intermediaries, addressing limitations of bulk suppliers' retail distribution capability (Commerce Commission New Zealand, 2022). This study focuses on the transport implications of DTS distribution, using real-world operational data to analyse manufacturer-led retail deliveries as opposed to contractor-managed third-party logistics.

### *2.2 Construction logistics*

Construction logistics manages resource flows from raw material processing to on-site use (forward logistics) and waste removal (reverse logistics) (Ding *et al.*, 2023). It involves on- and off-site systems and activities, including planning, organisation, transportation and site operations (Janné, 2018). Key logistical challenges include managing loading zones, material handling and storage and integrating multiple actors via transport networks (Fredriksson and Huge-Brodin, 2022; Janné, 2020; Dhawan *et al.*, 2023a). Construction contracts typically sub-contract work anywhere up to approximately 90% (de Graaf *et al.*, 2023). Each subcontractor, in turn, engages with multiple retailers (Deep *et al.*, 2024). The resulting coordination requirements and site storage constraints lead to complexities in on-site management (Dhawan *et al.*, 2024b).

Warehousing and transport are the core elements of construction logistics, with transport being the dominant component, as most other logistics activities involve business processes rather than physical ones (Dhawan *et al.*, 2023a). Manufacturer warehousing addresses temporal, spatial, quantitative and qualitative mismatches between material supply and demand across production, sales and consumption (Kondratjev, 2015). Intermediate, retailer-operated, warehouses buffer economic and logistical variations (Saderova *et al.*, 2021; Vidalakis *et al.*, 2011). Transport, on the other hand, links suppliers, intermediaries and construction sites (Naz, 2024; Janné *et al.*, 2018) through resource flows. Unlike general freight, construction transport is shaped by the fragmented and dynamic nature of projects, with demand driven by phase-specific resource needs (Sezer and Fredriksson, 2021; Guerlain *et al.*, 2018; Dubois *et al.*, 2019; Dhawan *et al.*, 2023b). Amongst these, construction materials, though low in unit value, are required in large volumes (Ying *et al.*, 2014), generating significant transport requirements even on small projects (Balm and Ploos van Amstel, 2018). Beyond energy consumption, emissions and costs, transport generates externalities – direct (noise, air pollution and congestion) and indirect (ecosystem damage, health impacts and reduced quality of life) (Chatziioannou *et al.*, 2020). In construction, these issues stem from both on- and off-site supply chain inefficiencies caused by information and coordination gaps, with poor integration across the supply chain-site interface leading to suboptimal delivery performance (Vrijhoef and Koskela, 2000; Fredriksson *et al.*, 2020; Dubois *et al.*, 2019).

From the main contractor's perspective, construction logistics aims to enhance on-site production efficiency by managing suppliers and deliveries around the central issue of limited on-site storage (Janné and Fredriksson, 2022). Construction projects demonstrate three types of fragmentation. Horizontal fragmentation manifests as multiple actors working within the same project stage, creating silos. Vertical fragmentation occurs across different stages (design, construction and operation), leading to discontinuities and misalignment. Longitudinal fragmentation refers to disaggregation of activities and resources across concurrently running projects (Riazi *et al.*, 2020; Jones *et al.*, 2022). While contractors can mitigate horizontal and vertical fragmentation, longitudinal fragmentation gets left out, as supplier-transporter interactions remain site- and delivery-specific (Janné, 2020). DTS distribution mitigates disruptions from fragmented contractor-led logistics by integrating the supply chain with the construction site through coordination for timed deliveries (Vrijhoef and Koskela, 2000).

### *2.3 Transport performance*

Transport is integral to business operations, with asset ownership and management invariably outsourced (Blancas and Briceno-Garmendia, 2020). Transport efficiency can be improved through strategic and operational tools (Dhawan *et al.*, 2022). However, evidence-based decision-making is constrained by the lack of comprehensive operational data (Mohapatra *et al.*, 2021), with commonly available data being trip-centric rather than supply chain focussed (McKinnon, 2015; Dhawan *et al.*, 2024a).

Transport planning is essential for optimising construction project productivity (Thunberg and Fredriksson, 2018; Lundesjö, 2018). The primary planning perspective is that of the main contractor (Eriksson and Fredriksson, 2025; Chau and Walker, 1994), who manages suppliers and deliveries around the central constraint of on-site storage (Lundesjö, 2018; Fredriksson *et al.*, 2022). By contrast, supplier-planned deliveries aggregate demand across multiple projects, improving load consolidation (Vidalakis and Tookey, 2005), thereby enhancing transport efficiency and reducing vehicle movements (Vidalakis *et al.*, 2011) and emissions (Dhawan *et al.*, 2024b; Dhawan *et al.*, 2024a). However, quantifying impacts of supplier-led logistics requires reliable operational data (Ferraro *et al.*, 2023).

Goods handling efficiency is influenced by vehicle performance at the operational scale (Pahlén and Börjesson, 2012). "Fill rate" refers to the ratio of transported goods to vehicle capacity (McKinnon, 2024; Abate and Kveiborg, 2013; McKinnon and Campbell, 1999). It operationalises metrics for assessing freight transport utilisation and efficiency, i.e. percentage of a trip during which the truck travels empty, ratio of weight carried to the payload capacity, achieved vs possible tonne-km, and the proportion of cubic or floor space used (Pahlén and Börjesson, 2012). This study uses two vehicle efficiency metrics: (i) Loads on trucks *vis-à-vis* their payload capacity at trip commencement ("loading efficiency") and (ii) Achieved vs potential tonne-kilometres ("capacity utilisation") (Pahlén and Börjesson, 2012).

Loading efficiency (expressed as percentage of payload capacity) is static and does not consider distances. Capacity utilisation in tonne-km reflects distance and load variation across trip segments (Barla *et al.*, 2010), shaped by factors such as application, vehicle type and operational constraints. Variability in load characteristics – weight, volume, direction, distance and time window requirements – makes utilisation context-dependent, even among similar vehicles (Abate and Kveiborg, 2013; Abate, 2013; Abate, 2014). Once considered waste, empty running is now a key sustainability concern, with policies and business metrics aiming to minimise it (Kohn and Brodin, 2008).

## 3. Methods and materials

This section presents the methodology for data acquisition and validation of its consistency, essential for the reliability of this study. Transport logs were used as the data source to ensure representativeness and reduce bias and noise, while standard statistical techniques adapted to data characteristics were used for validation.

### *3.1 Data acquisition*

The analysis uses three months (October–December 2020) operational transport data for DTS plasterboard distribution in Auckland, capturing 55 days of truck movements. This period reflects the post-COVID rebound of the New Zealand construction sector, making the data representative of typical BAU operations (NZ InfraCom, 2021). The data set included truck IDs, models, payload capacities, gross vehicle mass (GVM) and consignment details (quantities, loads, invoicing intermediaries and destinations). Distances between drop locations and their servicing sequence – both essential for transport efficiency analysis – were, however, not available (Dhawan, 2023). The need to incorporate these, while maintaining representativeness and ensuring computational feasibility, necessitated data sampling (Krejcie and Morgan, 1970).

A sample is a subset of data to estimate population characteristics, enabling faster analysis with acceptable accuracy and reduced processing. Simple random sampling ensures each element in the data set has an equal probability of selection, minimising bias and supporting valid statistical inference (Fox *et al.*, 2009; Rahi, 2017; Singh and Masuku, 2014). Krejcie and Morgan (1970) developed a nomogram for determining sample sizes based on population. Yamane (1973) and Cochran (1977) proposed alternative expressions that yield slightly larger sample sizes (Chaokromthong and Sintao, 2021).

Based on the data set of approximately 2,300 trips, Krejcie and Morgan's nomogram provides a sample size of approximately 340. However, considering the higher values of Yamane (1973) and Cochran (1977), a random sample of 370 trips was selected as a true representation of the full data set (Krejcie and Morgan, 1970) for ease of inserting distances and drop sequences. Hereafter, this subset is referred to as the "data sample" and the full set as the "complete data set". Distances required for the data sample were obtained from Google Maps and servicing sequences, from "Eroad" database, a New Zealand IT-based GPS service-provider.

### *3.2 Data validation*

Before sampling, the "normality" of transport operations needed to be validated. Transport operations are considered a function of random variables, such as delivery day/time, quantity and area and truck availability, capacity and allocation. Validating that loading efficiencies are normally distributed would indicate that dispatch planning is free from significant variation (Howard, 2003), implying no excessive influence of any underlying variable. Loading efficiencies were determined using consignment weight and truck capacity from the complete data set.

A Q-Q plot is a non-parametric method for assessing whether a sample follows a given distribution by graphically plotting sample quantiles ($y$-axis) against theoretical quantiles ($x$-axis). Alignment with line $y = x$ indicates conformity, while deviations indicate departure from the assumed distribution (Dhar *et al.*, 2010; Chambers, 2018; Alobaid and Corcho, 2024). Q-Q plots have been widely applied across various logistics contexts (Kimothi *et al.*, 2024; Enerstvedt, 2025; Dalla Chiara and Cheah, 2017; Bosso *et al.*, 2020; Aybalikh, 2024; Wu *et al.*, 2024) primarily to validate the statistical distribution underpinning a given data set. This study uses a Q-Q plot to assess whether the loading efficiency data was normally distributed. It uses the coefficient of determination ($R^2$), a stronger error detection metric than SMAPE, MAPE, MAE, MSE and RMSE (Chicco *et al.*, 2021), to measure goodness-of-fit (Dhar *et al.*, 2010). $R^2$ value of 0.9882, obtained using SPSS, demonstrated strong fit, indicating that dispatch planning was largely unaffected by variability from latent operational factors, subsuming them.

Optimisation models require consistent inputs to ensure outputs reflect systematic operations rather than random noise, enhancing reliability and interpretability. Cronbach's alpha, with values between 0 and 1 (Gliem and Gliem, 2003), assesses whether multiple discrete/continuous observations (Bravo and Potvin, 1991; Izah *et al.*, 2023) are consistent and reflect a single construct (Gliem and Gliem, 2003; Taber, 2018). This study used Cronbach's alpha to evaluate allocation coherence by assessing the internal consistency of dispatch planning, the construct of interest. The data set was structured as a matrix of daily allocation patterns, with columns representing days and rows representing individual truck (trip) loads. A tiered approach to the acceptability of alpha value has been suggested in the literature, with $\geq 0.9$ representing excellent and $\leq 0.5$ being unacceptable values of internal consistency (Gliem and Gliem, 2003; George *et al.*, 2003). The obtained value of 0.51230, at minimum acceptability, reflects operationally-driven stochasticity of truck allocation, variances in vehicle capacities and route demands and non-Likert data (Taber, 2018; Doval Dieguez *et al.*, 2023), differentiating it from random noise (Tavakol and Dennick, 2011; Santos, 1999; Bonett and Wright, 2015).

## 4. Analysis

The analysis compares plasterboard distribution strategies, uses the transportation model from operations research for optimisation, and assesses improvement in transport efficiency by applying the selected metrics. It further evaluates distribution-related carbon impacts and develops an "integrated warehousing" strategy using real Auckland locations and distances to measure decarbonisation potential.

### *4.1 The adopted plasterboard distribution strategy*

Plasterboard is a cost-effective, durable interior material valued for fire resistance, soundproofing and ease of transport, commonly used in residential and commercial partitions. Its customisable properties meet varied structural and acoustic needs (Esan, 2024). In New Zealand, plasterboard supply is highly concentrated, with one supplier holding approximately 95% market share. Most sales take place via BMs (Commerce Commission New Zealand, 2022), reflecting invoicing patterns rather than physical material flows through them.

The adopted distribution model (DTS) vertically integrates manufacturing and distribution, outsourcing transport to a second-party logistics (2PL) service provider (Ogorelc, 2007). Based on node-link theory (Speicys and Jensen, 2008), two information links (Site–intermediary and intermediary–manufacturer) support site material requirements and invoicing, while material flows along the third manufacturer–site link. This manifests the centralised "manufacturer storage with direct shipping" distribution strategy (Chopra *et al.*, 2013).

Quantifying distribution/supply chain design-based transport efficiency is a data-driven exercise (Ferraro *et al.*, 2023). The transportation data set revealed certain key parameters of distribution operations: approximately 330 tonnes of plasterboard distributed daily to construction sites; The fleet undertaking distribution comprised flatbed trucks from different manufacturers having varying payload capacities; On an average, 26 trucks undertook 42 trips daily for distribution; approximately 75% of trips involved deliveries to a single construction site; The number of trips having more than three drops was statistically insignificant; and, transport pricing by the contractor followed a "per-tonne" model regardless of distance (Dhawan, 2023).

The three nodes (Manufacturer–Intermediary–Site) form a triangle, with direct delivery (DTS) shorter than routeing through intermediaries – except when the three nodes are collinear, which is highly unlikely in urban settings. Analysis of DTS distribution revealed approximately 56.36% loading efficiency and approximately 27.61% capacity utilisation fleetwide, leaving approximately 252 tonnes of unused truck capacity daily, gainfully using only approximately 28% tonne-km. Loading efficiency and capacity utilisation were found to be sensitive to the number of drops per trip–increasing number of drops improved loading efficiency but reduced capacity utilisation (Figure 1).

### *4.2 Transport optimisation and its carbon impacts*

Logistics, being multidisciplinary, integrates strategies from diverse domains (Henrieta *et al.*, 2015). The challenge of optimising transport while maintaining delivery performance aligns with allocation problems, prompting the exploration of operations research for suitable optimisation tools. A literature review identified the linear programming (LP)-based transportation model as a potential solution (Silaen, 2019; Taha, 2013; Pečený *et al.*, 2020; Malacký and Madleňák, 2023). It represents supply and demand nodes connected by arcs subsuming routes, costs and quantities. The objective is to minimise transportation costs without exceeding supply capacities while fulfilling destination demands (Taha, 2013; Uzorh and Innocent, 2014). Other constraints such as delivery time windows, multi-drop trips and route-specificity can also be applied (Senthilnathan, 2014). Widely used in manufacturing and freight logistics contexts (Petropoulos *et al.*, 2024), application of the Transportation Model in construction remains limited to generic supply chain analyses and off-site production contexts (Chen and Hammad, 2023). Its application in the context of manufactured construction product distribution is, therefore, novel.

The transportation model was applied to optimise the initial basic feasible solution (Ahmed *et al.*, 2016), represented by the transport contractor's distribution plan. The case under examination, however, needed to be reformulated as it differs from the classical formulation due to the manufacturer's warehouse being the sole supply node, and decoupling of costs from distances (Dhawan, 2023) rendering the value proposition of cost minimisation irrelevant. The reformulation considers each truck as an independent source. Variable truck capacities reflect as "less than equal to" LP constraint (problem matrix rows) because a truck can carry up to this limit. Fluctuating construction site demands are incorporated as "equal to" LP constraints (problem matrix columns) because site requirements need to be met in full. Each cell in the problem matrix at the intersection of rows and columns reflects uniform per-tonne transportation costs.

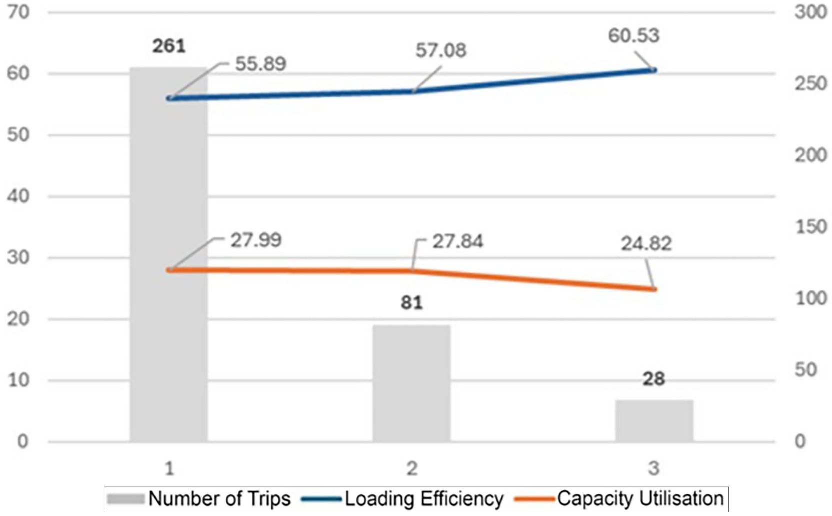

**Figure 1.** Transport efficiency sensitivity in DTS distribution

**Notes**: X-axis – Number of drops; Y-axis (left) – Efficiency in %; Y-axis (Right) – Number of trips

**Source**: Authors' own work

Conventional optimisation minimises total distribution costs through optimal routeing, because the per-unit cost associated with each route is different. However, when costs are small or uniform, flow minimisation, rather than route optimisation, becomes the primary operational performance driver (Ahuja *et al.*, 1988; Boffey, 1994; Dantzig and Thapa, 2003; Yahyaoui *et al.*, 2023; Yang *et al.*, 2024). The reformulation, therefore, transforms the cost minimisation problem to one of transport activity minimisation.

The MS Excel "Solver" add-in provides an accessible and reliable platform for solving transportation problems. Using the simplex LP algorithm, it efficiently minimises transportation costs under supply (truck capacity) and demand (site requirement) constraints. Excel's transparency supports easy validation and adjustment of model parameters, making it well-suited to applied logistics and operational research (Winston, 2004). Solver was used for "proof-of-concept" solutions, with data truncated to fit its 200-cell limit while preserving trip integrity. The solution matrix allocated a single truck's capacity to service multiple consumption points based on the defined constraints. Delivery time windows were, however, not considered because the deliveries were 24–48 h in advance and not JIT, based on advance planning of up to a month (Dhawan, 2023). Within the constraint of distance-independent transportation costs, reduction in the number of truck trips was used as a proxy for route optimisation.

Results showed that LP-enhanced DTS model reduced truck trips from 42 to 26, with a corresponding increase in loading efficiency from approximately 56.36% to 92.89% and capacity utilisation from approximately 27.61% to 49.38%. The resulting generalised trip model illustrated in Figure 2, represents an elemental, scalable distribution task, with each trip accounting for approximately 327 tonne-km.

The carbon impact of transport optimisation comprises two key elements: fuel savings from fewer truck trips and improved fuel efficiency through higher capacity utilisation. Estimating fuel savings involves calculating trip distances and average fuel consumption.

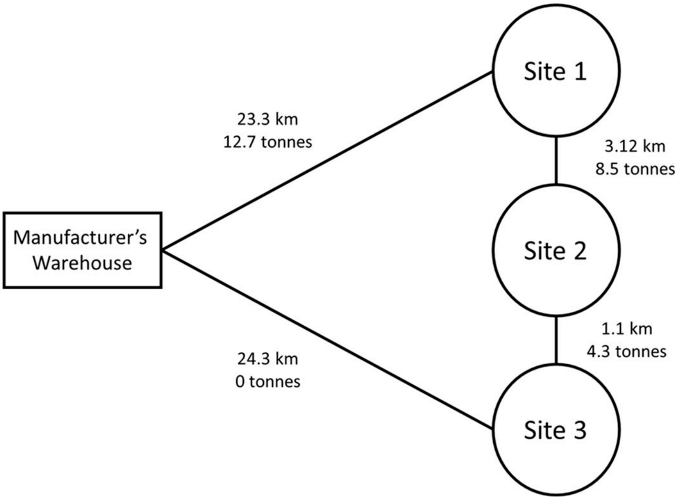

**Figure 2.** Generalised trip model
**Source**: Authors' own work

From the generalised trip model, trucks with an average payload of approximately 21.2 tonnes fall within the 20,000–24,999 kg GVM category, having average fuel efficiency of approximately 46.7 L/100 km (Wang *et al.*, 2019). A daily reduction of 16 trips of approximately 52 km each reduces approximately 832 km vehicle-kilometres-travelled, equating to approximately 388 l of diesel saved. Using New Zealand's diesel emissions factor of 2.69 kg $CO_2$-e/L (Ministry for the Environment, 2023), this results in a daily emissions reduction of approximatelt1043 kg $CO_2$-e.

Capacity utilisation exerts a stronger influence on truck fuel consumption than on other transport modes. The empirical model by Henningsen (2000) estimates fuel consumption (tonnes per kilo-tonne of cargo) against capacity utilisation over a 3,218 km control parameter. An extract of the graph illustrating a generalised performance curve for trucks, plotted between 40% and 100% capacity utilisation, is shown in Figure 3. Because it approaches the *y*-axis asymptotically below 40%, a linear extrapolation was applied to account for a minimum utilisation of 28% in this study. This, however, introduces an uncertainty band depending on whether linear extrapolation connects the original curve's endpoints or follows a tangent from its lowest point (dotted black lines in Figure 3). The red lines show *x*-axis intercepts between approximately 28% and 50% capacity utilisation. The solid and dotted green lines denote upper and lower fuel consumption bounds at approximately 28% capacity utilisation, while the turquoise line indicates fuel consumption at approximately 50% capacity utilisation per the original curve.

The best-case reduction in fuel consumption within this band is approximately 0.0074 kg/tonne-km (approximately 0.0082 L/tonne-km), and the worst-case is approximately 0.0050 kg/tonne-km (approximately 0.0055 L/tonne-km), corresponding to improvement in capacity utilisation from approximately 28% to 50%. For a 327 tonne-km (generalised) trip, this yields fuel savings of approximately 1.80–2.7 L/trip (approximately 47–69 L/day) and emissions reductions of approximately 127–186 kg $CO_2$-e/day at 2.69 kg $CO_2$-e/L per domestic New Zealand emissions benchmarks (Ministry for the Environment, 2023). The

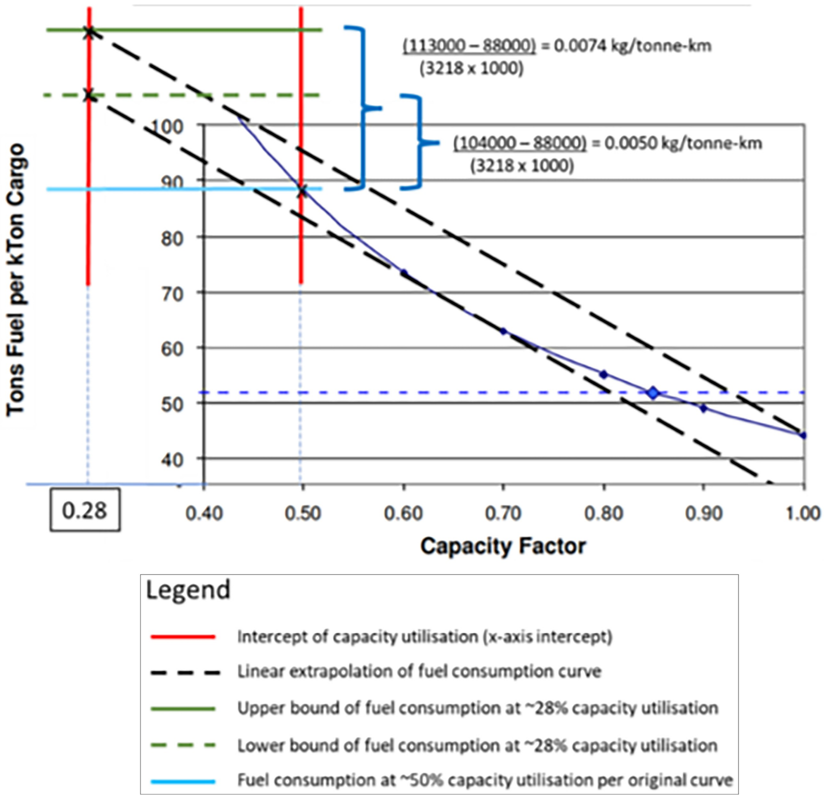

**Figure 3.** Superimposition of improved capacity utilisation on extract of Henningsen's plot
**Source**: Authors' own work

total daily emissions reduction achieved from reduced transport activity is, therefore, approximately 1,170–1,229 kg $CO_2$-e (1,043 kg $CO_2$-e from reduced trips and approximately 127–186 kg $CO_2$-e from enhanced capacity utilisation).

### *4.3 Integrated warehousing and its carbon impacts*

Urban sprawl tends to increase transport inefficiencies, particularly reduced capacity utilisation (tonne-km), due to longer round trips, smaller deliveries and lower load factors (Mohapatra *et al.*, 2021). Splitting delivery into two segments – one with approximately 100% capacity utilisation and the other with the DTS efficiency – can reduce distribution carbon footprint. A hybrid model delivering full truckloads (FTLs) to intermediary facilities, which serve as "forward" warehouses for DTS-based retail distribution to construction sites (Figure 4), offers a viable solution. Effective implementation depends on optimally locating these "forward" warehouses.

In Auckland, the shift of approximately 75% plasterboard delivery from FIS to DTS, has reduced stock levels at intermediary facilities, freeing up existing space (Dhawan, 2023). Freed-up space in comparatively larger intermediary facilities can be re-purposed to hold "forward stock" on a shared-capacity basis between the manufacturer and the intermediary,

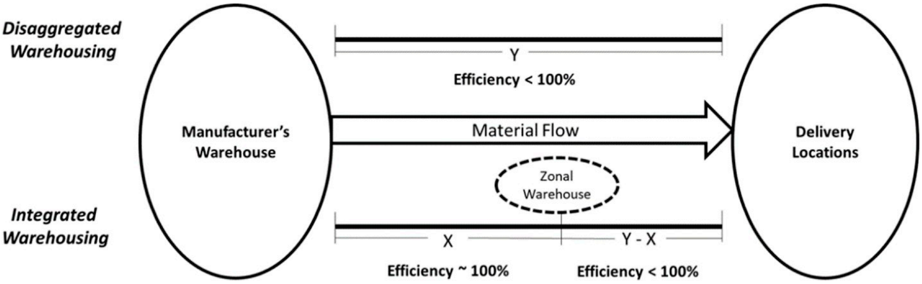

**Figure 4.** Improved transport efficiency with zonal warehouses
**Source**: Authors' own work

introducing "floating stock" into the supply chain, lowering storage costs and lead times while maintaining service levels (Dekker *et al.*, 2009). This shift of stocks reduces the manufacturer's warehousing space and real-estate requirements. Implemented as the "pooled warehouse" concept within collaborative logistics, this is an emerging area of research. Limited implementation has shown reduced costs and improved transport efficiencies (Makaci *et al.*, 2025; Makaci *et al.*, 2017).

Based on material uptake patterns and proximity to consumption points (Dhawan, 2023), inventory can be optimally placed in "centroidal" intermediary warehouses (Gehrlein and Pasic, 2009), adopting the centre-of-gravity (CG) approach (Zhao, 2014). Matching truck capacity to consignment size or standardising loads to truck capacities makes FTL transportation to "centroidal" warehouses feasible, effectively shifting a part of the trip to high-efficiency transportation with approximately 100% capacity utilisation. The relatively lower efficiency DTS segment is, therefore, confined to the final leg, minimising the overall transport activity (tonne-km).

For this analysis, Auckland was divided into five zones – centre, north, south, west and east – based on municipal boundaries. Delivery areas and material uptake were derived from intermediary invoicing data (complete data set), with Euclidean distances and bearings from an arbitrary zonal reference point measured via Google Maps. Bearing $x$ and $y$ components were weighted by material uptake (tonnage) to determine the displacement of each zone's CG from the assumed reference point. These CGs were refined using road network distances from Google Maps for calculating average CG-to-consumption point (construction site) distances. Results (Table 1) highlight Auckland's linear north-south sprawl.

The carbon impacts of integrated warehousing consider the LP-enhanced DTS model as the baseline. The LP-optimised trip (Figure 2) indicates that trucks with a GVM of approximately 15,000 kg (Wang *et al.*, 2019) are best suited for the 12.7-tonne load. With an average fuel consumption of approximately 31.52 l/100 km (Wang *et al.*, 2019), 26 daily trips of approximately 52 km correspond to approximately 426 l of diesel, resulting in approximately 1,146 kg $CO_2$-e of emissions. In the integrated warehousing model, long-haul trucks replenish zonal warehouses based on consumption. Assuming daily top-ups, Table 2 presents associated transport, fuel use and emissions, with round-trip distances from Table 1.

For further DTS distribution from the CGs, the average the round-trip distance is now approximately 21 km (Table 1). Adjusting the generalised trip model to 21 km round-trip, fuel consumption for 26 trips by < 15,000 kg GVM trucks is approximately 172 l (31.52/100 × 26 × 21), generating approximately 463 kg $CO_2$-e emissions. The daily emissions of

**Table 1.** Transportation distances for plasterboard distribution under "integrated warehousing"

| | Road distances | | | | | | |
|---|---|---|---|---|---|---|---|
| Zone | WH – Centroid | Centroid – Delivery areas | Centroid – CG | WH – CG | CG – Delivery areas | Total material uptake (55 days) | Daily uptake |
| Centre | 11.6 km | 4.42 km | 2.8 km | 9.5 km | 3.68 km | 980 T | 18 T |
| North | 23.1 km | 15.82 km | 2.2 km | 23.9 km | 15.73 km | 5618 T | 102 T |
| East | 12.0 km | 7.5 km | 6.4 km | 12.2 km | 4.78 km | 3429 T | 63 T |
| South | 22.2 km | 17.28 km | 7.9 km | 27.6 km | 17.22 km | 3336 T | 61 T |
| West | 1.2 km | 9.5 km | 1.0 km | 8.9 km | 9.4 km | 4511 T | 82 T |

**Note(s):** WH – Manufacturer's warehouse; Centroid – Assumed centroidal location; CG – Determined centre of gravity; T – Tonnes
**Source(s)**: Authors' own work

**Table 2.** Emissions from daily "topping up" of zonal warehouses

| Zone | Daily topping up (Tonnes) | Truck category (GVM) | Trips | Round-trip distance | Fuel consumption | Emissions |
|---|---|---|---|---|---|---|
| C | 18 | < 20,000 kg | 1 | 19 km | 7 l | Approximately 556 kg $CO_2$-e |
| N | 102 | >= 30,000 kg | 3 | 48 km | 80 l | |
| E | 63 | >= 30,000 kg | 2 | 25 km | 28 l | |
| S | 61 | >= 30,000 kg | 2 | 56 km | 62 l | |
| W | 82 | >= 30,000 kg | 3 | 18 km | 30 l | |

**Source(s)**: Authors' own work

the integrated warehousing model are approximately 1,019 kg $CO_2$-e (about 556 kg $CO_2$-e for "topping up" and approximately 463 kg $CO_2$-e for last mile DTS distribution), a reduction of approximately 127 kg $CO_2$-e on the LP-enhanced DTS baseline for the same delivery performance.

### *4.4 Overall impact on transport-related carbon embodiment*

The A4 LCA component was quantified to assess the impact of supply chain reconfiguration (integrated warehousing) on embodiment of carbon in plasterboard. using environmental product declarations (EPDs) (Winstone Wallboards, 2023), the analysis focused on fossil fuel-related global warming potential (GWP) (Papakosta and Sturgis, 2017) during distribution (A4 LCA stage). Because different types of plasterboard sheets have varying carbon footprints, supply ratios were used to calculate the average per-unit A4 carbon. Table 3 presents plasterboard sheet types, A4 GWP (fossil fuels) from EPDs and supply ratios from the complete data set (Krejcie and Morgan, 1970). Because the EPD was issued in 2023, the transportation component is DTS-based (Dhawan, 2023; Winstone Wallboards, 2023).

Analysis from Sections 4.1–4.3 shows emissions reductions of between approximately 1,170 and 1,229 kg $CO_2$-e from transport optimisation and approximately 127 kg $CO_2$-e from integrated warehousing when distributing approximately 330 tonnes of plasterboard daily. This represents a reduction of approximately $3.55–4.11 \times 10^{-3}$ kg $CO_2$-e per kg of plasterboard, equivalent to approximately 11.7%–13.6% decarbonisation from the baseline in Table 3.

**Table 3.** Plasterboard GWP (fossil fuel) for transportation (A4) stage

| | | | Transportation (A4) Carbon Component | | |
|---|---|---|---|---|---|
| Sheet thickness | Sheet type* | Per unit weight (kg/m$^2$) (EPD) | kg $\text{CO}_2$-e/m$^2$ (from EPD) | kg $\text{CO}_2$-e/kg (Calculated) | Supply ratio (%) |
| 10 mm | Type 1 | 7 | 2.01E-01 | 2.87E-02 | 36.62 |
| | Type 2 | 7.8 | 2.32E-01 | 2.97E-02 | 8.19 |
| | Type 3 | 9 | 2.72E-01 | 3.02E-02 | 6.91 |
| | Type 4 | 7 | 2.17E-01 | 3.10E-02 | 1.38 |
| | Type 5 | 7.2 | 2.16E-01 | 3.00E-02 | 0.36 |
| | Type 6 | 9 | 2.59E + 00 | 2.88E-01 | 0.12 |
| | Type 7 | 7 | 2.01E-01 | 2.87E-02 | 6.6 |
| 13 mm | Type 1 | 10.2 | 3.24E-01 | 3.18E-02 | 18.03 |
| | Type 2 | 12.4 | 3.70E-01 | 2.98E-02 | 4.06 |
| | Type 3 | 10.7 | 3.24E-01 | 3.03E-02 | 3.5 |
| | Type 4 | 8.7 | 2.63E-01 | 3.02E-02 | 5.85 |
| | Type 5 | 11.4 | 3.45E-01 | 3.03E-02 | 0.66 |
| | Type 6 | 9.1 | 2.75E-01 | 3.02E-02 | 0.48 |
| | Type 7 | 11.5 | 3.33E-01 | 2.90E-02 | 0.26 |
| | Type 8 | 8.7 | 2.63E-01 | 3.02E-02 | 0.43 |
| 16 mm | Type 1 | 13.7 | 4.56E-01 | 3.33E-02 | 2.64 |
| 19 mm | Type 1 | 16.5 | 5.07E-01 | 3.07E-02 | 0.62 |
| 25 mm | Type 1 | 20.2 | 6.59E-01 | 3.26E-02 | 3.28 |
| *Weighted average embodied A4 carbon per kg of plasterboard* | | | | | *3.03E-02* |

**Note(s):** *Proprietary/brand names of plasterboard have been masked
**Source(s):** Authors’ own work

## 5. Discussion

Supply chains manifest logistics sprawl in response to urban sprawl by relocating warehouses to peripheral areas (Heitz *et al.*, 2017). Theoretically, such shifts may reduce overall transport activity, however, empirical evidence to support this is lacking (Dablanc, 2007; Heitz *et al.*, 2017; Sakai *et al.*, 2017). Longer haul distances, though, are well substantiated (Gardrat, 2021), creating a spatial-efficiency paradox. As operational emissions decline in a zero/net-zero context, embodied carbon increasingly dominates the built environment’s carbon footprint (Chastas *et al.*, 2017). Achieving net zero targets within the LCA context, therefore, necessitates strategies for reducing embodied carbon (Arenas and Shafique, 2024). Among these, enhancing transport efficiency is critical, considering that approximately 5%–15% of a building’s total embodied carbon is transport-related (Hammond and Jones, 2008). However, realising such improvements is data-dependent, and is constrained by limitations of data availability, its variability and cost of analysis (US DoE, 2024; McKinnon and Campbell, 1999), necessitating a shift in construction logistics planning.

While manufacturing-stage bulk transport is efficient, the distribution phase – with fragmented retail flows, low load factors and deconsolidation inherent to contractor-managed deliveries – increases emissions substantially (Halldorsson and Wehner, 2020). One response is supplier-based consolidation, such as the DTS model, bypassing intermediaries by delivering retail volumes directly from manufacturer to construction sites (Vidalakis and Tookey, 2005; Vidalakis *et al.*, 2011). These enhance load consolidation (Vidalakis and Tookey, 2005; Dhawan, 2023), improve transport capacity utilisation and free up intermediary warehouse space, making it available for repositioning manufacturer's stocks closer to demand centres. This dual-stage model – bulk delivery to forward warehouses and DTS for last-mile distribution – can reduce both per-unit transport emissions and overall warehousing requirements.

This study investigates the transport function in construction logistics using the case of plasterboard distribution in Auckland, New Zealand. Auckland's linear, polycentric sprawl (Silva, 2018; Hoffman, 2019; Xu and Gao, 2021) has extended development away from the urban core (Silva, 2018; Richardson, 2022; Auckland Council, 2023), increasing haul distances between supply (freight generating) and demand (freight attracting) areas (Trent and Joubert, 2022; Gardrat, 2021). Consequently, established supply chains generate higher per-unit emissions, increasing A4-stage LCA embodied carbon (Balm and Ploos van Amstel, 2018; Lovell *et al.*, 2005).

Comparing BAU with a dual-stage model of bulk deliveries to zonal warehouses and DTS last-mile distribution, the analysis reveals the potential to optimise warehousing via manufacturer-intermediary capacity sharing as a result of delivery transport optimisation. It quantifies A4-stage LCA carbon reduction from transport efficiency gains and integrated warehousing, which consolidates forward-deployed stocks in demand-proximate warehouses (Trent and Joubert, 2022; Melo *et al.*, 2019; Skipper *et al.*, 2010; Dhawan, 2023), with the model adaptable to shifting demand patterns (Greenaway-McGrevy and Jones, 2023). Findings demonstrate that strategic distribution realignment facilitates manufacturer-intermediary resource sharing in response to logistics sprawl (Melo *et al.*, 2019), reducing the overall carbon footprint. Reduction in the overall transport activity under the proposed model is validated through comparison with plasterboard EPD baseline emissions. The study contributes to knowledge by analysing the interplay between distribution, transport and warehousing (Parikh *et al.*, 2010) in the context of linear sprawl, supporting transport-driven integrated warehousing capable of dynamic supply chain reconfiguration and shared logistics capacity.

The study's managerial contribution is in demonstrating the potential of a shift in construction logistics planning and early supplier involvement in the planning of site deliveries. It challenges the status-quo LCA approach which does not consider transport efficiency enhancements possible through improved planning and supply chain management (Naz *et al.*, 2022). The study also highlights the critical role of municipalities in regulating construction logistics and transport to address externalities for maintaining urban quality of life (Rönnberg *et al.*, 2023). It makes a policy contribution supporting the inclusion of logistics plans in consenting procedures and land agreements (Chau and Walker, 1994). The case study can be effectively integrated into university courses on logistics applications (Chen *et al.*, 2024), exemplifying the link between process waste reduction and built environment decarbonisation. Societally, the study supports integrating transport emissions into city sustainability targets to incentivise adoption of greener, cost-efficient practices, while shaping public perception of sustainable construction (Haag and Jünger, 2023; Chełstowska *et al.*, 2025).

Finally, the paper makes a theoretical contribution to construction management literature by demonstrating that traditional logistics planning, such as operations research tools for distribution, typically limited to manufacturing and freight, are applicable to construction despite its temporal and fragmented nature. Adopting a supplier perspective of construction logistics, that defragments the construction supply chain and unlocks efficiency gains, is also a contribution to the predominantly contractor-centric construction management literature.

## 6. Conclusion

This study quantifies the carbon impacts of the complex interplay between distribution, transport and warehousing, using real-world operational data to address a key research gap. It transforms transport activity analysis to evaluate embodiment of carbon in plasterboard, and by extension, the built asset. Drawing on plasterboard EPDs, product supply ratios and New Zealand emissions benchmarks, the study estimates an approximately 11.7%–13.6% reduction in embodied carbon. The findings provide hard evidence of reduced transport movements achieved through load consolidation in supplier-managed distribution, demonstrating how adaptive supply chain configurations can reduce transport activity in response to urban sprawl.

Despite its novelty, the study has certain limitations. Its focus on manufactured construction products limits applicability to bulk material supply chains, while the context of Auckland's urban conurbation may limit transferability to other regions, products, or market structures. Reliance of retrospective optimisation on an initial human-derived solution simplifies computational complexity but may restrict efficiency gains compared to algorithmic optimisation. Additional uncertainty may arise from methodological choices, such as extrapolation of fuel parameters, and from operational variances in actual fleet deployment.

The study contributes to the growing body of evidence demonstrating that systemic, interdisciplinary approaches are essential for developing sustainable and efficient supply chains under increasing resource constraints. It establishes a framework extendable to outsourced transport for stock replenishment at zonal warehouses, integrated reverse logistics for plasterboard waste management, zonal warehouses acting as consolidation points in the waste removal chain, elimination of redundant transport for waste handling and reuse of plasterboard waste as raw material for manufacturing. Contextually, the analysis can inform sustainability assessments of manufactured construction product supply chains and the wider freight transport sector. This work also opens several avenues for future research such as quantifying sustainability outcomes (e.g. emissions, congestion and fuel use), assessing direct/indirect economic impacts, evaluating scalability across regions and materials, and examining emerging technologies such as artificial intelligence-based routeing and Internet of Things-enabled fleet management for improved sustainability performance.

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