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Monetised sustainability impacts of integrated planning in the manufactured construction products industry: A transport perspective from New Zealand

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ABSTRACT

The extensive, interdisciplinary nature of construction supply chains make them prone to inefficiencies at organisational interfaces. Inefficiencies are accentuated by the project-centric delivery paradigm, and complex logistics systems between multiple stakeholders. They manifest as a multitude of concurrent activities, processes, and systems both on and off-site. Transportation is the largest component of the logistics domain. Transport operations are inherently fragmented, intrinsic to every business, while vehicle ownership and deployment is typically externalised. Differentiated waste removal and materials delivery further disintegrate the already fragmented construction supply chain. Inefficiencies from the insularity of the planning process across segmental boundaries aggregate incrementally, with impacts visible at the macro level. Re-configuration of activities, resources and actors are acknowledged strategies for optimising logistics and transportation function. This paper investigates the impact of three integration strategies on a manufactured construction products supply chain efficiency. These strategies include vertical integration of distribution, integrated planning for transport operations, and integration of reverse logistics into operations. Sustainability impacts are evaluated according to domestically determined monetary parameters to benchmark performance at the business and national scale.

KEYWORDS

Integrated planning; construction logistics; sustainable freight transport; sustainability monetisation; transport externalities

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1. Introduction

Construction contributes approximately 13% to Gross Domestic Product (GDP) globally (Barbosa et al., 2017). Construction is significant in generating employment, enhancing infrastructure, and supporting businesses. Its activities are crucial for socio-economic progress, leading to significant consumption of resources. Construction accounts for 36% of global energy consumption and 39% to global emissions (Santamouris & Vasilakopoulou, 2021). Despite its size, construction is notoriously fragmented (Guerlain et al., 2019; Jones et al., 2022; Riazi et al., 2020; Shakantu & Emuze, 2012). This manifests in two ways: i) Globally the industry is populated by numerous competing small firms; and, ii) From a project perspective, there is a disaggregation of construction processes and entities (Alashwal & Hamzah, 2014; Alashwal & Fong, 2015).

Logistics - including transportation, warehousing, and inventory management - is a critical interdisciplinary aspect of Construction Supply Chains (CSC). Logistics significantly impacts project management and costs (Ying & Tookey, 2014) with CSC fragmentation leading to inefficiencies in coordination and integration at organisational boundaries (Alashwal & Fong, 2015). Process inefficiencies increase resource overheads, raising sustainability concerns. Transport constitutes the largest component of logistics (Bowersox et al., 2002; Bowersox & Closs, 1996; Madadi et al., 2010), due to most logistics processes (excluding warehousing) being business rather than physical processes (Szymonik, 2012). High-volume and low-value nature of construction materials (Balm & Ploos van Amstel, 2018; Lovell et al., 2005) implies that transportation is pre-eminent within construction logistics. Transport requirements, even for relatively small projects, can be considerable.

Apart from considerations related to energy consumption, emissions, and costs (Smith et al., 2002; Szymonik, 2012; Ying et al., 2014), there are other transport-related externalities in sustainability. These may be immediate and direct (pollution, noise, traffic congestion etc), or indirect (disruption of ecosystems, health consequences, poor quality of life) (Chatziioannou et al., 2020). The wide array of impacts indicates the potential for improved sustainability outcomes through optimisation of transport - particularly since the contribution of transport to emissions is ~60% by 2050 (Edenhofer, 2015). Analysis confirms that transportation is a particularly difficult sector to decarbonise from challenges in scaled deployment of options and extremely high dependence on fossil fuels (Guerin et al., 2014; McKinnon, 2018).

New Zealand (NZ) has multiple logistics challenges (Dani et al., 2022), including geographical isolation, elongated physical layout (Silva, 2018), thinly distributed population, small economy, import reliance, and low demand-consumption patterns (Khan & Lockhart, 2019; Naismith et al., 2016). This leads to circa 93% of freight transportation occurring via road - of which over 30% is construction-related (Ministry of Transport New Zealand Government, 2020a). The complex NZ market dynamics impede adoption of advanced technologies - compounding existing challenges (Ministry of Transport New Zealand Government, 2020a). Government strategy for combating climate change prioritises freight transport decarbonisation to achieve NZ's 2030/2050 carbon targets, through a Avoid-Shift-Improve framework (Bongardt et al., 2019; Ministry of Transport New Zealand Government, 2021). Three themes are applied - one focussing on freight transport. Supply Chain (SC) efficiency, optimised transport, collaboration and data sharing, and legislation are identified as implementation enablers (Ministry of Transport New Zealand Government, 2021).

The research gap indicates that freight decarbonisation implies examining logistics planning as a tool for improved sustainability. The overarching research question being addressed in the study is the impact of integrating business processes (supply chain models, planning, and logistics activities) on transport efficiency. The paper addresses these through quantification of transport efficiencies achieved from vertical integration of distribution, integrated transportation planning, and integration of reverse logistics into the transport operations of a narrow CSC segment (plasterboard) in NZ.

The study contributes to the knowledge corpus of construction logistics by quantifying the inherent transport inefficiencies in NZ construction logistics, a first-principles approach to improve it, and an extrapolation of the improvements to assess their dollar value using NZ-specific parameters. Based on an extensive literature review, the authors consider this to be the first study of its kind in NZ.

2. Baseline definition

The baseline for this paper is defined along four axes:

- The construction logistics problem.
- The materials delivery supply chain.
- Assessment of freight transport efficiency.
- Problem description and analysis.

2.1. Construction logistics

Construction logistics coordinate, control, and manage the flow of products, from processing of raw materials to final application in a project, and reverse logistics of waste removal and disposal (Agapiou et al., 1998; Ying & Tookey, 2014). Multiple stakeholders comprise construction logistics, engaged on- and off-site in wide-ranging activities, processes, and systems. These can be grouped into three domains of organising and planning, transportation, and on-site activities (Janné, 2018, 2020; Janné et al., 2018). Efficient construction logistics require planning, management of loading and unloading zones, warehousing (internal and external to the construction site), on- and off-site materials handling, and transportation linking actors and channels of the logistics system (Ekeskär & Rudberg, 2016; Janné, 2018; Janné & Fredriksson, 2019; Janné et al., 2018).

Construction logistics is typically viewed from the contractor's perspective, who need to manage all suppliers and site deliveries, with the principal constraint of storage space. On-site logistics coordination addresses a project's horizontal (disaggregated skill sets/expertise) and vertical (well-defined phases) fragmentation issues. It is, however, incapable of addressing longitudinal fragmentation (between projects) since the supplier and the transporter are independent entities, coming together only for site-centric deliveries. The perspective from the supplier's end, however, reverses. Supplier managed deliveries effectively get consolidated. They demonstrate higher efficiencies as compared to business-as-usual (BAU), with the added benefit of managing more than one sites within the planning boundary. Therefore, in part addressing longitudinal fragmentation of the sector.

2.2. Materials delivery supply chain

The CSC has three primary actors. The bulk suppliers (including manufacturers) and the construction site represent the two ends, with Builders' Merchants (BMs) providing interim storage and consolidation. The supply of construction materials and components typically adopts three models: i) Direct to customer (Direct-to-Site - DTS); ii) Sale of a limited product range through specialist stockists; and, iii) Bulk or retail sales through BMs (Freight-into-Store - FIS) (Commerce Commission New Zealand, 2022):

- The DTS model is invariably adopted for large consignments (steel framing etc.) not requiring intermediaries.
- Supply through specialist stockists is a mechanism adopted by manufacturers for marketing products through their own subsidiaries.
- The FIS model works for most situations where bulk suppliers cannot effectively manage retail quantities.

In the FIS model, BMs supply a variety of essential construction materials, with significant over-the-counter deliveries. These pertain to both 'heavy' (sand, bricks, blocks, and aggregate) as well as 'light' (fixtures, fittings, tools, plumbing, and heating supplies) materials. BMs are also the principal economic dampers of the CSC by extending a line of credit to contractors and holding safety stocks to absorb market fluctuations. Inventory holding costs can be anywhere up to 20% of inventory costs (Agapiou et al., 1998; Bowersox et al., 2002; Dhawan, 2023; Vidalakis & Tookey, 2005; Vidalakis et al., 2011).

BMs may operate at the national, regional, and local merchant level. Those operating at a national scale typically have national and/or regional distribution centres. Irrespective of the scale of operations, customer interfacing takes place through local depots/warehouses serving specific geographical areas. The transport function of these depots is not an entity in itself; rather, it is a derived demand for customer delivery. The depot vehicle fleet is typically small and serves a local customer network (residents, construction sites, and larger construction businesses or organisations). Planning of delivery trips is based on the staff's knowledge about the local routes and locations (Dhawan, 2023).

Regional and national merchants maintain centralised control over their fleet, which is managed by a transport professional. In the case of BMs, the fleet is typically managed by the depot manger, who is not a transport professional. Customer delivery is the focal point, and not transport efficiency. The order cycle usually commences a day in advance for the ensuing day's work (Commerce Commission New Zealand, 2022; Dhawan, 2023). Efficiency, or rather inefficiency, gets cloaked in 'hidden costs' of construction material (Balm & Ploos van Amstel, 2018; Verlinde, 2015; Ying & Tookey, 2014).

2.3. Transport efficiency measurement

The efficiency of goods handling is determined by filling rate, vehicle efficiency, freight transport efficiency, and system efficiency (Pahlén & Börjesson, 2012). The first and second are operational/tactical, while the third and fourth are strategic. This study is built upon the concept of filling rate, defined as, *"the ratio of the actual goods moved to the maximum achievable if the vehicles, whenever loaded, are loaded to their maximum loading capacity"* (McKinnon, 1999). In the case of a truck, vehicle utilisation (the ratio of the vehicle capacity utilised to the available vehicle capacity) narrows down to five measures (McKinnon, 2010; Pahlén & Börjesson, 2012):

- **Level of empty running** Proportion of the distance travelled empty.
- **Weight-based loading factor** Ratio of the actual weight carried by the truck to the maximum weight it can carry (the rated payload capacity).
- **Tonne-km loading factor** Ratio of the actual tonne-km transported to the maximum possible tonne-km (based on the rated payload capacity). Unlike weight-based loading, which assumes a constant loading factor on a trip, tonne-km-based loading is dynamic as it varies with delivery or collection of consignments along the route.
- **Volumetric loading factor** A three-dimensional perspective of vehicle fill that considers proportion of the total cubic capacity of the vehicle occupied by the load.
- **Deck-area coverage (or 'load area length')** A two-dimensional view of vehicle loading that considers proportion of the vehicle floor (or deck) area covered by a load. In case of loading height limitations, deck area limits loading instead of cubic capacity.

Transport efficiency depends upon vehicle capacity utilisation across onward and return trips. Finding backloads for returning transport is a major logistical challenge in the construction sector. Empty running of vehicles, earlier considered waste, has now graduated from an environmental liability to a sustainability issue (Kohn & Brodin, 2008). Consequently, from a policy and business model perspective, reducing empty running is the key focus of most sustainable distribution strategies (McKinnon & Ge, 2006).

2.4. Problem description, data availability, and research questions

Evidence-based decision-making in the construction freight/logistics domain is constrained by dearth of relevant data. Typically available data relates to individual freight journeys with a general lack of SC perspective (McKinnon, 2015). This presents a barrier to quantifying efficiency enhancements and analysing potential for further improvement potential as a consequence of implemented SC models.

2.4.1. Problem description

The problem under investigation pertains to the supply of plasterboard in Auckland by NZ's largest manufacturer. In the BAU scenario, distribution takes place through a disaggregated SC with three nodes of interest - the manufacturer's warehouse, the BM network, and the construction sites. The FIS model has two links (Manufacturer – BM and BM – Construction Site) linking three nodes for both information and material flows. Each node has storage as one of its primary functions. This model has substantial time and space associated with the intermediate node (the BM), where material arrives in bulk from the manufacturer or bulk supplier and departs in bulk or retail to consumers (Commerce Commission New Zealand, 2022). It is a manifestation of 'Distributor storage with carrier delivery' logistics model from the literature (Chopra et al., 2013).

The modified (DTS) model involves forward vertical integration (VI) of distribution with manufacture and outsourcing of transport on a second-party logistics (2PL) basis. It presents three nodes and three links, as opposed to the FIS model. Two of these are information links for invoicing and delivery (Contractor – BM, BM – Manufacturer). The third link handles physical transportation of material (Manufacturer – Site). Invoicing is done by the BM, based on which the manufacturer delivers the material directly to site. DTS represents 'Manufacturer storage with direct shipping' logistics strategy (Chopra et al., 2013).

2.4.2. Data availability

Three months' operational transport data (October 2020 to December 2020) pertaining to DTS delivery of plasterboard formed the basis of this study. The dataset included truck IDs, specifications (payload capacity and Gross Vehicle Mass - GVM), and consignment details (items, quantities, loads, and destinations). The distances involved and the drop sequence were not available. The dataset presented the following characteristics:

- 26 trucks of different payload capacities undertook 42 trips for transporting 330 tonnes of plasterboard on an average daily.
- Each truck made one to six drops per trip.
- The number of trips with more than three drops comprised less than 1% of the dataset, considered insignificant for the analysis.
- Approximately 75% of the trips had a single drop.
- Material transportation costs were 'per-tonne' across Auckland, irrespective of the distance.
- The trucks employed were all diesel powered flat-bed trucks from four different manufacturers.

2.4.3. Research questions

Ostensibly, the DTS solution delivered higher service efficiency and customer satisfaction compared to the FIS model. The improvement had, however, not been quantified. This leads to the following research questions:

RQ1. What is the transport efficiency improvement achieved by DTS deliveries over the FIS model?

RQ2. What is the potential for further improvement and the means to achieve it?

RQ3. How can reverse logistics be integrated, and how much improved transport efficiency would this result in?

RQ4. What is the monetised value of sustainability benefits achieved from improvement in transport efficiency and what is the likely economy-wide impact on the manufactured construction products SC?

3. Research design

Based on the overarching research question and the specific inquiries, the case study research design was considered appropriate since the inquiry (transport efficiency and monetisation) is data-driven and evidence-based. Quantitative methods were the primary analysis tool, supported by qualitative instruments for validation. The primary data source was the operational transport data logged by the firm. Secondary data came from the IT services supplier, Google Maps, and NZ-specific parameters from the domestic research repository of New Zealand Transport Agency (NZTA) and the Ministry of Transport, New Zealand Government. Semi-structured interviews with the concerned functionaries enabled understanding the operational philosophy and implemented supply chain models and permitted interim milestone results. Triangulation was achieved through discussion with the logistics management functionaries. Figure 1 illustrates the research design adopted.

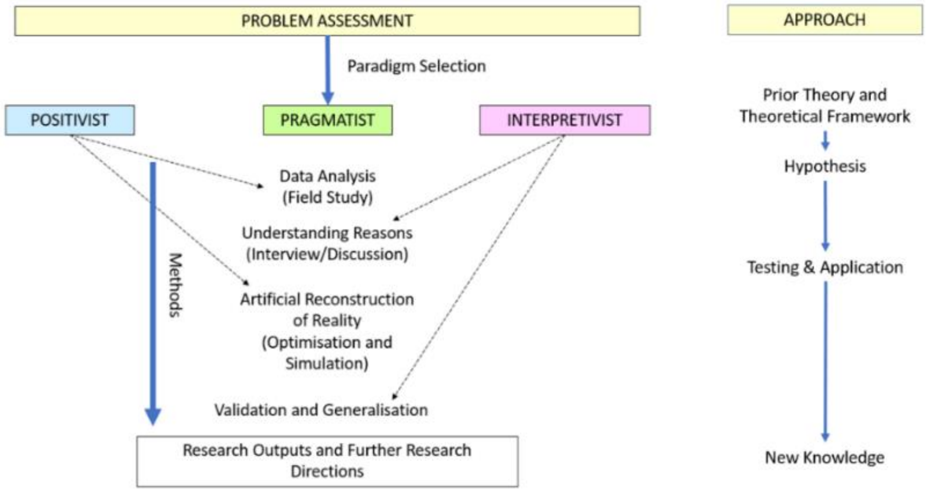

Figure 1. Research design.

3.1. Data analysis

Before data analysis was undertaken, the reliability of the dataset was ascertained by determining its 'normality' using SPSS. The dataset best fitted the normal curve with a slight skew. Cronbach's-α was used for testing data sample consistencies prior to undertaking the analysis (Dhawan, 2023; Dhawan et al., 2023). The fundamental attributes of quantitative analysis were fulfilled as follows:

- **Reliability** The data collection and analysis satisfied all three attributes of reliability, i.e. Homogeneity (the measured parameters being distances and loads carried, sufficient to describe transport efficiency); Stability (standard and reliable tools for measuring efficiency parameters *viz* a calibrated weighbridge for loads, and distances measured using Google Maps); and, Equivalence (the distances between fixed points on the ground, and the loads measured being constant irrespective of the viewer, preventing subjectiviey in perception) (Heale & Twycross, 2015; Neuman, 2014).
- **Validity** Data collection involved minimum subjective inputs from the researcher, the participants, and/or other personnel. The collation of operational data by the logistics department is considered robust since transport operations impact the firm's business model directly. Further, data analysis aims were clearly

articulated, i.e., to find efficiencies based on distances travelled by trucks and the further potential for improved efficiencies by applying statistical/management techniques. Certain data recording errors were removed through 'cleaning-up' data before analysis without impacting the sample size (Cook et al., 2002; Heale & Twycross, 2015; Trochim, 2000).

- **Generalisability** The inquiry has four constructs impacting its generalisability, i.e., data sampling, transport, freight, and the construction domain. *Statistical generalisability* is achieved through random sampling, with sufficient data points precluding any clustering or stratification errors. It also supports generalisability to the manufactured construction products segment in NZ. *Analytical generalisability* is achieved by the potential applicability of results to freight operations in other domains (industries) or contexts (long-haul, short-haul, and last-mile delivery). In addition, *case-to-case transferability* can be achieved by the application of results to manufacturer-to-consumer transport in other industries (e.g., manufacturing and urban distribution) (Firestone, 1993; Polit & Beck, 2010; Yin, 2004).

3.2. Assumptions and limitations

The following assumptions underpin the analysis undertaken:

- There exists an intrinsic inefficiency in construction transport, which stems from the inherent fragmentation of the construction and transport domains.
- The transportation model under consideration is deterministic and does not consider temporal stochasticities.
- The transportation system aims to maximise tonnages delivered and minimise delivery time.
- There is no pattern in the employment of trucks; availability and allocation are random.
- The effect of data sampling and truncation is only marginal on the solution achieved, compared to if the complete dataset were used.
- Transport operations are heuristically planned.
- The planning solution provided by the software tools is adequately optimised, without considering solutions from variants of the model used (Transportation Model).

The study has the following limitations:

- It pertains to a narrow segment of the CSC, associated with manufactured construction products. The outcomes may not be fully indicative of the implications for the CSC at large (especially for bulk materials such as aggregate, steel etc.).
- The operational data, and therefore, the analyses undertaken are specific to Auckland, which is a typical manifestation of a an 'elongated sprawl'. The results may not be entirely applicable to other regions with a 'squarer' physical expanse.
- The work undertaken is retrospective, i.e., the data pertained to operations already performed.
- The optimisation model is based on operations 'as-executed'. Hence, any future optimisation needs to commence with human intervention in configuring operations, however inefficient it may be, to be followed up with an optimisation exercise. This reduces the computing power and the complexity of algorithms required for achieving optimisation (e.g., application of transportation model on operations scheduled through human intervention vis-à-vis application of, say, a Vehicle Routing Problem algorithm).
- Integration of reverse logistics does not consider the temporal displacement between fresh material supply and waste generation on-site. The mechanisms for integrating reverse logistics need to be worked out separately.
- The sustainability impacts and monetisation are broad estimates, indicative of the existing potential.

4. Transport efficiency analysis

4.1. Transport efficiency measures

The two measures selected for analysing transport efficiency in this paper are the weight-based and tonne-km-based loading factors (termed 'loading efficiency' and 'capacity utilisation' respectively). The former is static, being a measure at a point in time (dispatch), without considering distances involved. The latter is dynamic as it includes loads and distances across the complete trip. Since the dataset did not include distances and drop sequences, a statistically significant sample was extracted as a true representative of the trip population for introducing these parameters. Random (probability) sampling was used to extract a sample size of 370 trips as true representation of an infinite trip population (Krejcie & Morgan, 1970).

4.2. Quantifying efficiency improvement of DTS model over FIS model

As a result of VI, the DTS model modifies the transportation network by eliminating one node and one link in the transport network. Figure 2 illustrates the transport network in the FIS and DTS configurations.

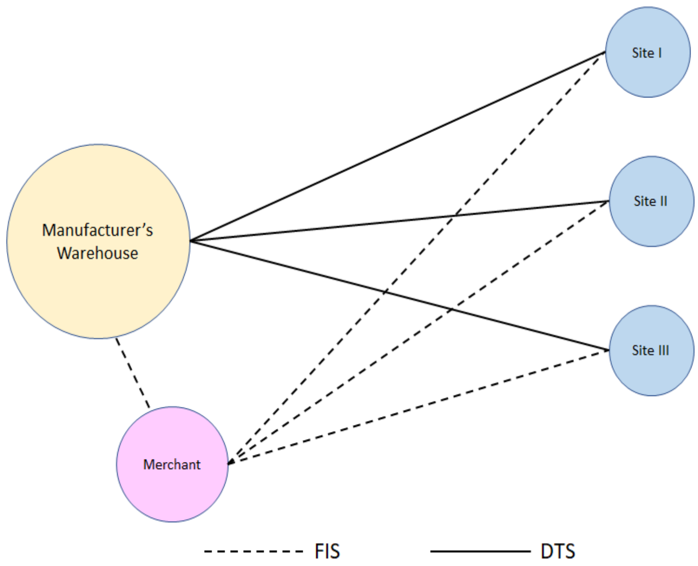

Figure 2. Transport network configurations for the FIS and DTS distribution models.

Considering that the three links joining the three nodes form a triangle, the length of any one link will always be less than the sum of the other two unless all three nodes lie on the same line. However, actual manifestations of road and destination networks are rarely composed of straight lines. A reduction in distances travelled in the DTS model compared to those under corresponding FIS deliveries for each BM-destination combination was used as a straightforward assessment parameter for efficiency improvement. The distances between various nodes along a trip were obtained from Google Maps. The aggregated results are presented in Table 1.

Table 1. Quantification of reduction of distances in the DTS model over the FIS baseline.

Parameter	DTS (km)	Ratio of DTS to FIS distances
Average	27.04	0.7086
Maximum	119.1	2.19
Minimum	3.8	0.1047

Individual BM-destination distances were considered for the analysis since circa 75% of the truck trips in the dataset involved a single drop. Instead of presenting the distances travelled individually in the DTS and FIS models, a ratio of the distances presents a stronger indication of improved efficiency. The analysis revealed a reduction of 30% translating to 11.1 km per trip between the FIS and DTS models. Though pertaining to a specific CSC segment (plasterboard distribution) in the Auckland setting, the improvements provide a benchmark for the construction products SC.

4.3. Potential for further efficiency improvement

For investigating further potential for efficiency enhancement within the DTS model, the problem was formulated as, "*Assessing the potential for improved efficiency of 'Direct-to-Site' transport operations for plasterboard supply in Auckland, NZ, proposed to be addressed through operational data analysis.*" The sequence of drops was introduced in the data sample from the 'Eroad' (a private IT services company in NZ providing GPS enabled tracking services) database. Based on distances between nodes, the drop sequence, the loading efficiency at dispatch (static), and the loads for individual destinations along a trip, the tonne-km based capacity utilisation (dynamic) was analysed (Table 2).

Table 2. Loading efficiency and capacity utilisation of trucks vis-à-vis the number of drops (DTS).

Drops	Trips	Loading Efficiency			Capacity Utilisation		
		Maximum	Minimum	Average	Maximum	Minimum	Average
1	261	99.21	4.31	55.89	49.61	2.16	27.99
2	81	99.77	6.45	57.08	55.79	3.33	27.84
3	28	90.33	14.99	60.53	42.11	4.93	24.82
Weighted Average (fleetwide)				56.36			27.61

The following are inferred from the above analysis:

- Underutilisation of circa 252 tonnes of available truck payload capacity daily, resulting in non-utilisation of nearly 72% available tonne-km.
- Requirement of improved transport planning to reduce the number of daily truck trips without adversely impacting delivery capacity.

4.4. Operations Research as a potential solution

Being multidisciplinary, logistics draws strategies and tools from various domains (Hrablik et al., 2015). In the instant case, application of Linear Programming (LP) (Transportation Model) from operations research was explored as an optimisation tool. The basic design of a transportation problem is composed of a network with sources and destinations represented by nodes, and shipping routes, quantities of material, and the per unit shipping cost represented by arcs connecting nodes (Taha, 2013). It aims to minimise the cost of satisfying the requirements of the destinations within the existing supply capacity of the origins (Uzorh & Innocent, 2014).

The problem under consideration, however, presented certain peculiarities that differentiated it from a standard transportation problem. It, therefore, needed reformulation as follows:

- Disaggregation of the data sample dataset into sub-datasets comprising a single day's operations.
- Instead of the manufacturer's warehouse, each truck trip was taken to be a source with supply capacity equal to the truck's rated payload.
- Each delivery undertaken during the day was taken to be a consumer (demand).
- The channel cost (per unit transportation cost) was assumed to be unity (being fixed), due to actuals being

commercially sensitive. Any other positive number would work equally well.

The 'Solver' add-in to MS Excel was used for solving the transportation problem using LP. 'Solver' has a restriction of not more than 200 objective co-efficients in the problem matrix. Since the exercise was a 'proof-of-concept', the dataset was truncated to include as many truck trips as possible per day within the limitations of the number of objective co-efficients, while maintaining trip integrity (i.e., without truncating any trip). The parameters applied were:

- Total load to be delivered *equal to* the summation of the node demands.
- Total load to be delivered *less than or equal to* the trip capacities.
- The objective co-efficients (per unit channel costs) assumed to be *unity*.
- The objective function taken to be *cost minimisation*. With constant channel costs, the model transforms to a resource (transport) minimisation tool.

The matrix was then solved for decision variables (allocation of loads to trucks). The resulting transport optimisation achieved is shown in Table 3.

Table 3. Transport optimisation (improved efficiency) using LP.

Parameter	Manual truck allocation	LP based truck allocation	Improvement (%)	
			Absolute	Over manual baseline
Average loading efficiency (dispatch)	56.36%	92.89%	36.49%	64.81%
Daily truck trips	11	7	-	36.36%
Capacity utilisation (tonne-km)	27.61%	49.38%	21.77%	78.84%

The number of daily trips in the LP optimised results works out to about 26 pro-rata (extrapolated from 7 in the results), eliminating 16 truck trips daily (on a baseline of 42). This has a two-pronged impact:

- Reduced number of trucks on the road without reducing the delivery capacity.
- Enhanced capacity utilisation of trucks from 27.61% to 49.38%, due to improved loading efficiency.

Application of LP revealed the need for integrated planning. In the status quo, the manufacturer's aim was transportation of ordered quantities of plasterboard daily. The employment of resources was entirely at the discretion of the transport contractor due to the 'per-tonne' payment model. There was no imperative for resource-use analysis, as long as the daily tonnages were delivered. Maximising transport utilisation becomes an imperative under two conditions: i) The payments model is distance-based (per-km); or, ii) Introduction of the sustainability context in transport operations. Both conditions introduce the need to minimise distances travelled by trucks. Integrated planning with the involvement of the manufacturer, even if only for monitoring transport utilisation, is an outcome.

4.5. Integration of reverse logistics

The capacity utilisation of trucks for a single drop trip is likely to be at best 50% and less than 50% for trips with more than one drops (Vrijhoef, 2015). Besides the trucks moving back empty to the origin from the last drop location, sequential unloading at various destinations along the route generates capacity for backloads (Berden & van Amstel, 2017; Shakantu & Emuze, 2012). This presents a fertile opportunity for backhaul of plasterboard waste from construction sites. The potential for backhauls needs to be considered from the perspectives of waste plasterboard arisings on-site and the potential for picking up this waste without using additional transport.

Based on estimates by Jacques (1999), Gade & Seadon (2022), and Nelson et al. (2022), 20% plasterboard waste from each construction site is considered a fair estimate. Reverse logistics can be effectively integrated by utilising truck payload capacities generated as a result of dropping consignments along the route for picking up waste.

A generalised model to include number of trips per truck, load per trip segment, and per site per truck waste arisings needed to be formulated for evaluating the potential to improve truck capacity utilisation through integrated reverse logistics. The model considered average distance and load figures from the sampled dataset, and approximate plasterboard waste arisings based on material delivery. The distances are presented in Table 4.

Table 4. Distance parameters for the generalised trip.

Drops	Trips	Average distances (km)			
		WH – Drop 1	Drop 1 –Drop 2	Drop 2 – Drop 3	Last drop – WH
1	261	22.76	0	0	22.76
2	81	24.92	10.55	0	28.22
3	28	23.67	11.84	16.16	32.6
Weighted Average		23.29	3.21	1.22	24.62

Notes: WH – Supplier's Warehouse

The data sample informs an average of 12.7 tonnes of plasterboard delivered to each site, averaging at 4.24 tonnes per drop across three deliveries. 20% waste arisings indicate about 850 kg of waste associated with each delivery, which can be picked up by the truck supplying fresh material during the subsequent delivery. Table 4, combined with optimised (LP based) delivery and waste loads results in a generalised trip model at Figure 3.

The progressive efficiency enhancement utilises 326 tonne-km after applying LP, and 393 tonne-km with backhauls of waste plasterboard, out of approximately 672 tonne-km available per trip. This translates to an improved efficiency of 49.38% and 58.04% respectively, from 27.61% (DTS baseline).

5. Sustainability benefits and their monetisation

5.1. Sustainability contributors and monetisation benchmarks

From the analysis so far, sustainability benefits accrue from the following individual contributors:

- Indirect costs: -
  - Reduction in vehicle-km as a result of the adoption of the DTS model over the FIS model.
  - Improved loading and capacity utilisation of trucks through application of LP-based planning.
  - Reduction in the number of trucks as a consequence of improved loading.
  - Improved capacity utilisation of trucks as a result of integration of waste removal with forward delivery.
  - Improved performance (higher fuel efficiency) of diesel engines from improved loading.
- Direct costs: -
  - Savings in ownership and operational (O&O) costs.
  - Savings in costs from reduced diesel consumption.

The NZ-specific benchmarks forming the baseline for monetising external sustainability impacts of the above are tabulated at Table 5. The parameters/statistics have been obtained from domestic research documents/reports, duly cited.

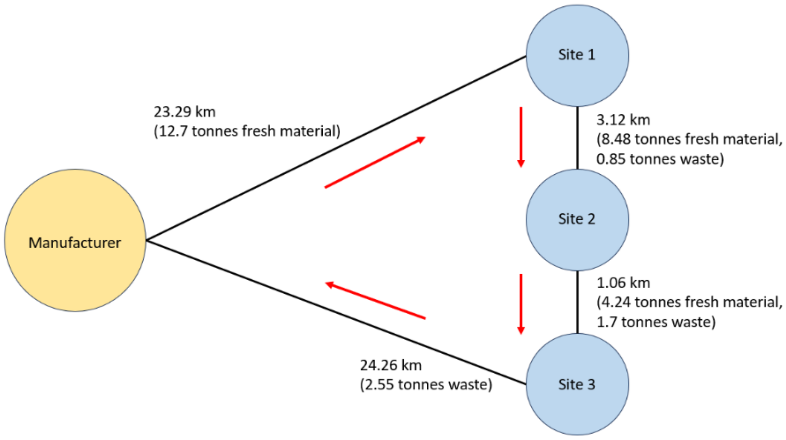

Figure 3. Generalised trip model representing the DTS plasterboard distribution operations with integrated waste removal from site.

5.2. Sustainability benefits of individual contributors

5.2.1. Reduced fuel consumption from adoption of the DTS model over the FIS model

As a result of adopting the DTS model, there is a reduction of about 30% (11.1 km) reduction in distance travelled per truck trip (Table 1). The data sample revealed an average payload capacity of 21,170 kg per truck, based on specifications obtained from the NZ Vehicles Register. This was compared to a previous NZ-based study conducted between 2015 and 2018 by Wang et al. (2019), which categorised the NZ truck fleet by GVM, and assessed the nationwide average fuel efficiency for each, irrespective of individual loading (Figure 4).

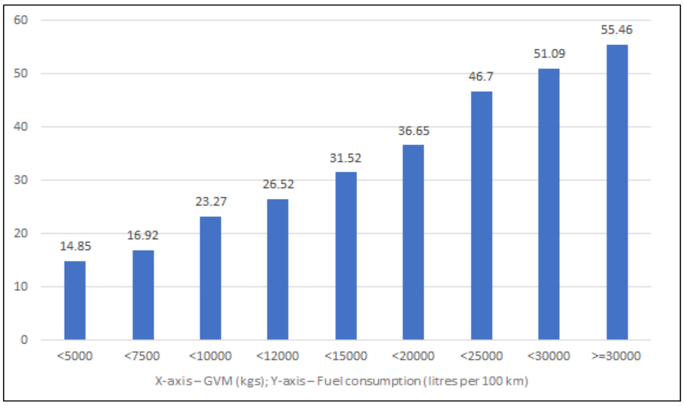

Figure 4. Generalized fuel efficiencies of various GVM categories of trucks in NZ (Wang et al., 2019).

Table 5. Monetisation benchmarks for sustainability impacts of transport contextual to NZ.

On account of	Impact or value	Based on	Data source (s)	Analysis equivalence	Monetised impact per km
Annual gain in GDP and balance of payments	NZ$4.37 billion per annum	30% fuel supply to convert to biofuels from 2020-2040 (@ 1.5% per annum); 53.4% diesel consumed by freight vehicles (from fleet composition); 3 billion annual freight km	(Massey University, 2023b; Ministry of Business Innovation and Employment New Zealand Government, 2021; Ministry of Transport New Zealand Government, 2020a, 2020c)	Reduced fuel consumption; Reduced vehicle-km	NZ$1.47/km

Social cost of damage by freight transport (from emissions)	NZ$520 million per annum	Transport sector share of social cost of damage NZ$2.1 billion per annum; 24.8% transport emissions from freight transport	(Climate Change Commission New Zealand, 2021; Ministry for the Environment New Zealand Government, 2022; Ministry of Business Innovation and Employment New Zealand Government, 2021)	Reduced fuel consumption; Reduced vehicle-km	NZ$0.173/km
Cost of deaths due to freight transport	NZ$693 million per annum	51.5 deaths per billion freight km; 3 billion annual freight km; NZ$4.47 million monetised cost of death	(Briggs et al., 2016; Ernst & Young, 2021; Massey University, 2023a)	Reduced fuel consumption; Reduced vehicle-km	NZ$0.231/km
Carbon savings for every tonne-km shifted to rail/shipping		NZ$76.85 cost of CO2-e per tonne; Approximately 107g of CO2-e savings for every tonne-km of mode shift; 9.64 tonnes average loading of freight transport	(Ernst & Young, 2021; Ministry of Transport New Zealand Government, 2022)	Reduced vehicle-km	NZ$0.079/km
Air quality and GHG costs from HGV	NZ$673.9 million per annum	3 billion annual freight km	(Ministry of Transport New Zealand Government, 2023)	Reduced fuel consumption; Reduced vehicle-km	NZ$0.157/km
Congestion costs per vehicle km removed from roads	-	Simple average of congestion costs/vehicle-km in various regions of NZ; 48.4% vehicle kilometers travelled (VKT) on local roads; 6.47% VKT from freight	(Ministry of Transport New Zealand Government, 2020b, 2020d; New Zealand Transport Agency, 2023)	Reduced vehicle-km	NZ$0.95/km
				Total	NZ$3.06/km

The average payload capacity of 21,170 kg fits neatly into the GVM category of 20,000 kg to 24,999 kg (<25000 kg), with an average diesel consumption of 46.7 litres per 100 km. A reduction of 11.1 km translates to 5.18 litres of diesel per trip. Considering 42 trips a day, the overall daily reduction in diesel consumption is 217.56 litres. @ 247 working days annually, the reduction in vehicle-km is 126,100 km converting to 53,700 litres reduction in diesel consumption annually.

5.2.2. Reduced fuel consumption due to LP-based reduction of truck trips

The number of truck trips reduce by 16 (from 42 to 26), i.e., by about 38%, through LP-based planning. Considering the generalised trip length of 52.3 km, 16 trips convert into approximately 836 km per day, and, @247 working days, to about 206,700 km annually. Considering the status quo average GVM of trucks as being in the 20,000 - 24,999 kg category, 206,700 km annually convert to a reduction of 46.7 x 206,700.00 / 100 = 96,524 litres of diesel per annum. Reduction in fuel consumption is concurrent with the reduced vehicle-km.

5.2.3. Reduced fuel consumption due to improved engine performance from LP-based optimisation

The reduction in fuel consumption from improved truck loading is reckoned from the work of Henningsen (2000), which quantifies improvement in engine performance based on improved loading. It presents a plot of the approximate fuel consumption of various modes of transport in tonnes per kilo-tonne of load (y-axis) for various capacity utilisation factors (x-axis), over 3,218 km (control parameter). In the instant case, the truck capacity utilisation improves from 27.61% to 49.38% due to LP-based optimisation. Superimposing these figures on

Henningsen's plot provides an estimate of fuel savings. For reckoning, the original fuel consumption curve for trucks has been modified with a linear variation as extrapolating the original plot to 29% tends to make it asymptotic to the y-axis. A linear plot overcomes this limitation, also providing conservative estimates. The reduction in fuel consumption is reckoned by superimposing capacity utilisation data from Table 3 on the plot (Figure 5).

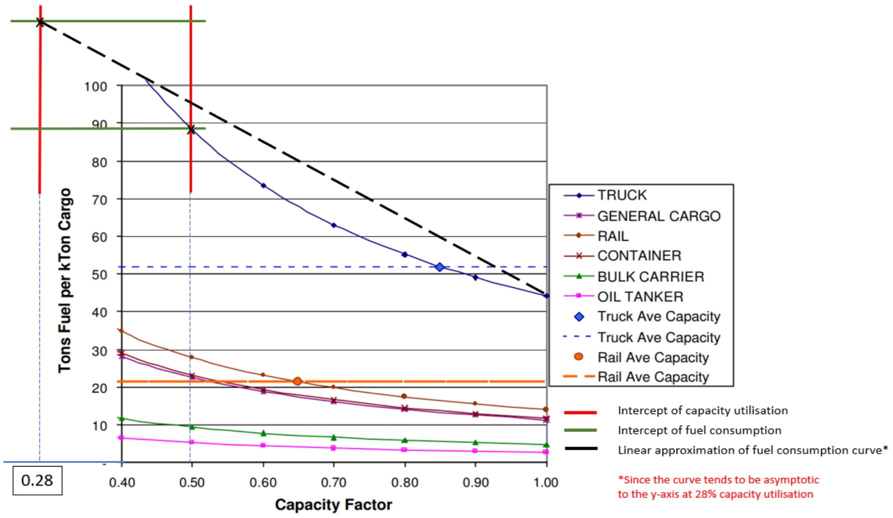

Figure 5. Estimation of reduction in fuel consumption due to improved capacity utilisation of trucks (Henningsen, 2000).

The y-axis intercept between the green lines translates to a reduction of about 0.0074 kg/tonne-km (0.0082 litres/tonne-km) in diesel consumption [(113,000 – 88,000)/(3218 x 1000) kg/tonne-km]. For a truck carrying 12.7 tonnes of load from the generalised trip model, the reduction in fuel consumption works out to 0.1057 litres of diesel per km. Over 52.3 km per trip, the reduction is 52.3 x 0.1057 = 5.53 litres. 26 trips daily, over 247 working days annually translate to approximately 35,500 litres of reduced diesel consumption per year.

5.2.4. Reduced fuel consumption from improved capacity utilisation due to integration of reverse logistics

In this case, the improvement of capacity utilisation from 49.38% to 58.04% is superimposed on Henningsen's (2000) (Figure 6).

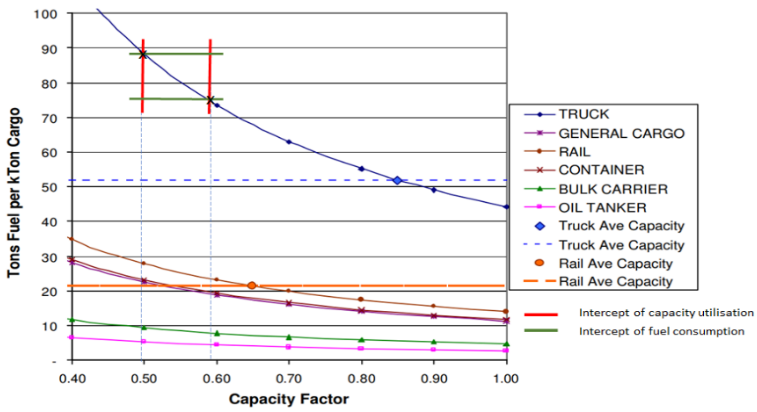

Figure 6. Estimation of reduction in fuel consumption due to integration of reverse logistics of waste removal (Henningsen, 2000).

This analysis uses the original plot since capacity utilisation factors lie within its original limits. The intercept between the green lines is converts to about 0.004 kg/tonne-km (0.0044 litres/tonne-km) of reduction in diesel consumption [(88,000-75000)/(3218 x 1000) kg/tonne-km]. For a vehicle carrying 12.7 tonnes of load (the generalised truck), it converts to 0.059 litres of diesel per km, or 2.92 litres of diesel over 52.3 km trip length. A daily reduction of approximately 76 litres results for 26 trucks. Over 247 working days annually, this translates to a reduction of 19,674 litres of diesel consumption per annum.

5.3. Monetisation of sustainability benefits

Before attributing monetised values, the individual parameters (vehicle-km, fuel) from the above analyses need to be converted to the other, for application to the individual benchmarks from Table 5. This is shown in Table 6.

Table 6. Conversion between vehicle-km and fuel.

S. No.	Reason for improved transport efficiency	Impact parameters				Conversion based on
		Vehicle-km	D or I*	Fuel (litres)	D or I*	
1.	Adoption of DTS model over the FIS model	126,100	D	53,700	I	BAU truck GVM
2.	LP-based reduction in truck trips	207,600	D	96,524	I	
3.	LP-based improved capacity utilization	112,627	I	35,500	D	Reduced truck GVM
4.	Integration of reverse logistics	62,418	I	19,674	D	

Notes: D – Direct calculation; I – Indirect (calculated by conversion); Annual vehicle-km – Direct 333,700 km; Indirect – 175,045 km.

The applicability of the above direct and indirect parameters to the individual benchmarks depends upon the impact being considered. E.g., the congestion cost uses only the vehicle-km reduced from direct calculation, with those reckoned by converting fuel reduction into vehicle-km being irrelevant. To the contrary, social cost of damage from emissions can use the directly reckoned vehicle-km as well as the equivalent reduction in fuel consumption. Table 7 presents applicability of impact parameters to NZ benchmarks, converted to vehicle-km, since the cost benchmarks have reckoned per km.

Table 7. Monetisation of sustainability impacts.

S. No.	Benchmark parameter	Applicability of vehicle-km (D and I)*	Numerical value	Cost per km (from Table 5)	Monetised value (per annum)
1.	Annual gain in GDP and balance of payments	D + I	508,745	NZ$1.47/km	NZ$747,855.00
2.	Social cost of damage by freight transport (from emissions)	D + I	508,745	NZ$0.173/km	NZ$88,012.00
3.	Cost of deaths due to freight transport	D + I	508,745	NZ$0.231/km	NZ$117,520.00
4.	Carbon savings for every tonne-km shifted to rail/shipping	D	333,700	NZ$0.079/km	NZ$26,362.00
5.	Air quality and GHG costs from HGVs	D + I	508,745	NZ$0.157/km	NZ$79,873.00
6.	Congestion costs per vehicle km removed from roads	D	333,700	NZ$0.95/km	NZ$317,015.00
				Total monetised benefits	NZ$1,376,637.00

Notes: D – Direct calculation; I – Indirect (calculated by conversion).

In addition to the above, the direct O&O costs are NZ$3.01/km on a 2018-19 baseline (Ministry of Transport New Zealand Government, 2023). Applying the Reserve Bank of NZ inflation calculator (Reserve Bank of New Zealand, 2023) shows an increase of 20 cents to the dollar for obtaining the current O&O costs. Reduction of 333,700 km annually results in savings of O&O costs of approximately NZ$1,201,320 (@ NZ$3.60/km). Reduced diesel consumption of 55,174 litres translates to another approximately NZ$104,800 per annum (@ NZ$1.90 per litre).

6. Extrapolation of monetised impacts to the wider NZ economy

6.1. Assumptions and baselines

To be able to extrapolate the analysis on the manufactured construction products segment and the wider NZ economy, the following parameters have been taken as the baseline in the context of residential construction:

- The total construction activity in NZ as at June 2022 was NZ$31 billion. Of this, residential construction contributed NZ$5.8 billion, representing about 18.7% (Ministry of Business Innovation and Employment New Zealand Government, 2022).
- Materials account for approximately 19% of residential building costs, with plasterboard taking approximately 0.5% share (Deloitte, 2018).
- The largest supplier of plasterboard in NZ holds approximately 95% market share (Commerce Commission New Zealand, 2022; Nelson et al., 2022). Hence, the baselines of calculation/reckoning sustainability benefits from the plasterboard case study can be safely assumed to be valid across NZ.
- Transport costs may amount to as much as 50% of the materials cost in construction (Vidalakis & Sommerville, 2013; Vidalakis et al., 2011) and between 10% and 20% of construction costs (Building Research Establishment, 2003).
- In the case of plasterboard, transportation costs may be taken to be between 8%-12% (average 10%) of the material cost. The same is assumed for other manufactured construction products except roofing (Deloitte, 2018).
- A third of the annual freight-km in NZ, circa 1 billion vehicle-km, are construction related (Ministry of Transport New Zealand Government, 2020a).
- The average O&O costs per km across all truck categories in NZ is approximately NZ$3.01/km during 2018/19 (Ministry of Transport New Zealand Government, 2023). The external costs are approximately NZ$3.06/km (from Table 5).
- From the Reserve Bank of NZ inflation calculator, the cost of transport has increased by about 20 cents to each dollar (Reserve Bank of New Zealand, 2023). Hence, the current per km O&O costs of transportation may be taken to be approximately NZ$3.60/km.
- The transportation costs for bulk materials such as cement and steel in NZ are on the higher side due to consumption points being very far away from sources (manufacturing plants). Hence, these are left outside the scope of the subsequent analysis.

The above benchmarks/statistics are used for analysing the impact of transport optimisation in the manufactured construction products segment on the wider NZ economy as under:

- Manufactured residential building materials, other than bulk materials and roofing, contribute to about 15.3% of the construction costs in NZ (Deloitte, 2018).
- Transportation cost of these works out to 1.53% of NZ$5.8 billion @10% of material costs (Deloitte, 2018), i.e., NZ$88.74 million.
- At NZ$3.6/km, this corresponds to approximately 24.64 million km annually, across the forward and return trips. This is about 0.25% of construction transport's annual contribution to freight-km (1 billion km).
- The median fuel efficiency of a diesel truck (across all categories) in NZ is approximately 41-42 litres/100

km, with the median GVM lying between 20,000 kg and 25,000 kg (Wang et al., 2019). This validates the average GVM of trucks in the plasterboard case study.

- The average load on a truck in NZ is 9.64 tonnes (Ernst & Young, 2021).
- Considering the median GVM as representative of the NZ truck fleet, the payload capacity is assumed to be about 19,000 kg (from the difference between GVM and tare weight).
- 9.64 tonnes equal about 50.7% loading efficiency. This may be taken as the BAU scenario since it has been arrived at from generalised statistics across the NZ freight sector.
- 50.7% loading efficiency translates into about 25.4% capacity utilisation assuming that all trips are single drop trips. This is an assumption from the NZ CSC configuration and the FIS model in vogue (Commerce Commission New Zealand, 2022). Considering multiple drops is likely to change it only marginally, assuming they are in the same proportion as the plasterboard case study (about 75%).
- At 24.64 million km, with a standard 9.64 tonne loading, the annual utilised tonne-km for the manufactured construction products for the residential market works out to 118.765 million tonne-km against 468.18 million tonne-km available capacity.

Due to the inability to formulate a generalised trip model from lack of exhaustive operational data, impacts of per unit improvement in capacity utilisation are discussed as follows:

- Capacity utilisation of trucks can be improved either by increasing the load on trucks, or by reducing their payload capacity for the same loads (to reduce the ratio of utilised to available capacity).
- Assuming that the loads are based on the demand of manufactured products and are constant, each percent decrease in available tonne-km (by reducing truck capacity while keeping the km constant at 24.65 million annually) on the baseline 468.16 million annual tonne-km results in an improvement of capacity utilisation by about 0.26% on the baseline 25.4% existing capacity utilisation (1% upward movement).
- In absolute terms, a 50% reduction in truck payload capacities will result in a 25% improvement in capacity utilisation, which agrees with the return trip being empty.

6.2. Sustainability impacts and their monetisation

Henningsen's (2000) plot is again used for analysing the likely reduction in fuel consumption due to improvement in loading efficiency, and therefore, capacity utilisation. As in section 4.2.3, the truck fuel efficiency curve here also is approximated by a straight line, so that the fuel consumption at about 25% capacity utilisation can be plotted conveniently. The consumption at 50% capacity utilisation is plotted on the original curve (Figure 7).

From the plot, the reduction in fuel consumption (y-axis intercept), on improving capacity utilisation from 25% to 50% is approximately 30 tonnes of fuel per 1000 tonnes of cargo over 3218 km. For each percent improved capacity utilisation, this works out to 0.373 gm/tonne-km or 0.439 ml/tonne-km. For 118.765 million tonne-km annually, the reduction in diesel consumption is approximately 52,138 litres per percent improved capacity utilisation. This benchmark, along with relevant outcomes from the plasterboard case study will be applied to obtain an estimate of the economy wide monetised sustainability impacts. The baseline annual vehicle-km for the CSC segment under consideration is 24.64 million km.

Table 8 presents the fuel and vehicle-km parameters for calculating the monetised impacts. It does not consider integration of reverse logistics as a contributory factor to improved transport capacity utilisation since most manufactured construction product wastage rates on construction sites are likely to be much lower than plasterboard. Application of plasterboard wastage rates is likely to skew analysis.

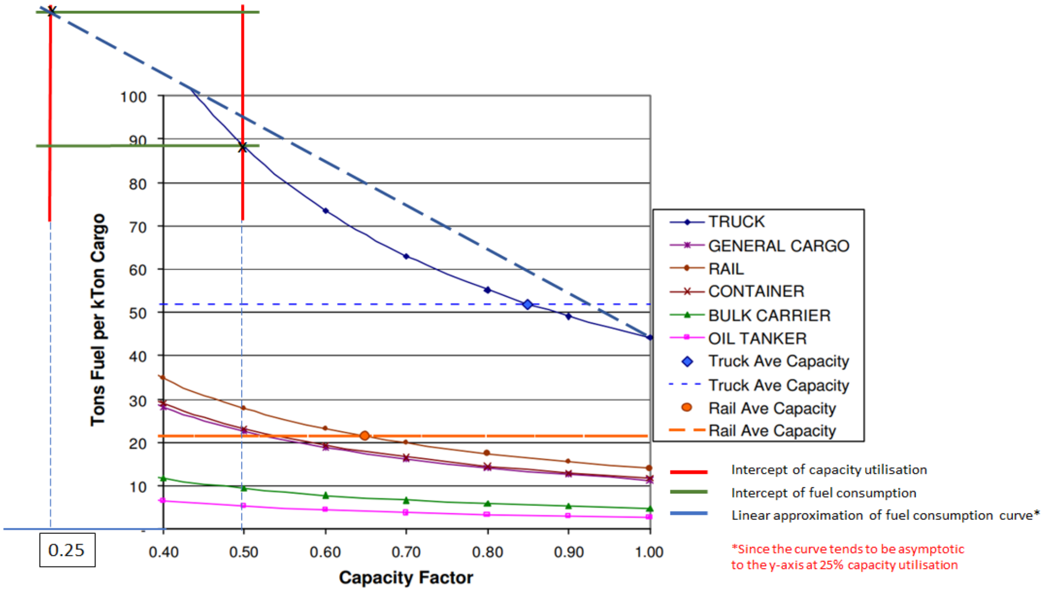

Figure 7. Estimation of reduction in fuel consumption due to improved capacity utilisation of trucks in the generalised freight operating model (Henningsen, 2000).

Table 8. Conversion between vehicle-km and fuel.

S. No.	Reason for improved transport efficiency	Basis	Impact parameters				Baseline
			Vehicle-km	D or I*	Fuel (litres)	D or I*	
1.	Adoption of DTS model	30% reduced vehicle-km	7,392,000	D	3,472,000	I	24.64 million annual vehicle-km; Table 1
2.	LP-based reduction in truck trips	38% reduced vehicle-km	6,550,000	D	3,059,000	I	DTS baseline for km; 46.7 litres per 100 km for fuel
3.	LP-based improved capacity utilization	21% improved capacity utilisation	2,345,000	I	1,095,000	D	Table 3

Notes: D – Direct calculation; I – Indirect (calculated by conversion); Annual vehicle-km – Direct 333,700 km; Indirect – 175,045 km.

Table 9 monetises the sustainability impacts based on parameters from Table 5 and Table 8.

Table 9. Economywide monetisation of sustainability impacts.

S. No.	Benchmark parameter	Applicability of vehicle-km (D and I)*	Resulting km	Cost per km (from Table 5)	Monetised value (per annum)
1.	Annual gain in GDP and balance of payments	D + I	16,287,000	NZ$1.47/km	NZ$23,941,890.00
2.	Social cost of damage by freight transport (from emissions)	D + I	16,287,000	NZ$0.173/km	NZ$2,817,651.00
3.	Cost of deaths due to freight transport	D + I	16,287,000	NZ$0.231/km	NZ$3,762,297.00
4.	Carbon savings for every tonne-km shifted to rail/shipping	D	13,942,000	NZ$0.079/km	NZ$1,101,418.00
5.	Air quality and GHG costs from HGVs	D + I	16,287,000	NZ$0.157/km	NZ$2,557,069.00
6.	Congestion costs per vehicle km removed from roads	D	13,942,000	NZ$0.95/km	NZ$13,244,900.00
				Total monetised benefits	NZ$47,425,225.00

Notes: D – Direct calculation; I – Indirect (calculated by conversion).

In addition, direct reduction of 13,942,000 vehicle-km results in reduced O&O costs of approximately NZ$50,191,200 annually (@NZ$3.60/km). The cost savings from reduced diesel consumption works out to approximately NZ$2,080,000 per annum (@ NZ$1.90/litre). The economy wide annual monetised impact of sustainability outcomes from potentially improved transport efficiency in the manufactured construction products sector pertaining to residential construction in NZ is approximately NZ$52.27 million in direct costs and NZ$47.42 million in external costs. The analysis is indicative due to the large number of assumptions and approximations made, and a wide range of information sources used.

7. Results and discussions

The overarching research question sought quantifying the impact of integrating business processes on the efficiency of the transport function of logistics, allocating a dollar value, and evaluating the economy-wide impact. The study analysed transport efficiencies in the manufactured construction products segment, using plasterboard distribution in Auckland, NZ as a case study. Progressive application of improved supply chain models (DTS model vs FIS model), integrated planning (use of operations research-based tools), and integration of reverse logistics for plasterboard demonstrates improved transport efficiencies (Figure 8).

Secondary data from domestic research sources was used for quantifying the dollar value per km. The monetisation cost components used are shown at Figure 9.

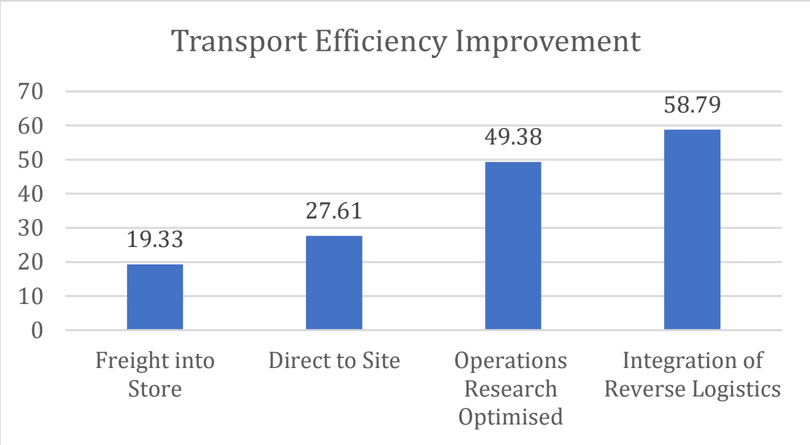

Figure 8. Progressive transport efficiency improvement.

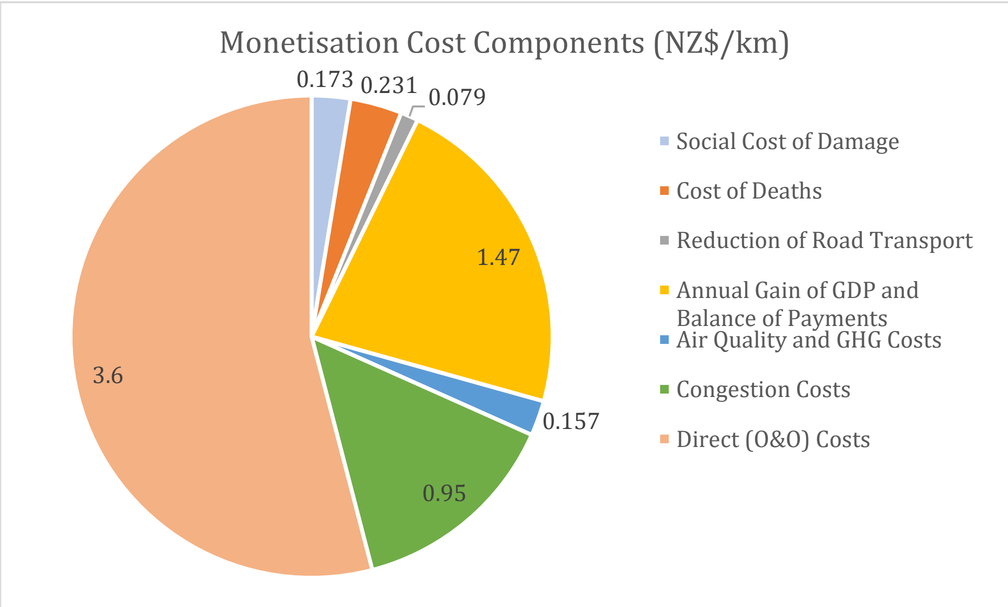

Figure 9. Monetisation cost components.

Monetised impacts for two situations have been analysed in the paper. The first, pertains to the plasterboard distribution case study, and the second, to the economy-wide extrapolation of the results of the case study for a specific construction industry segment (residential construction). Integration of reverse logistics has not been considered as a contributory factor for the economy-wide impacts. This is due to the likelihood of skewing the analysis as a result of the likely difference in the wastage rates of plasterboard and other manufactured construction products due to their nature. However, the additional aspect of reducing truck sizes for the same carried loads has been considered as a contributory factor. Table 10 illustrates the reduction in distances and fuel consumption for the plasterboard case study and its extrapolation to the wider economy.

Table 10. Comparison of improved efficiencies (km and fuel) for plasterboard case study and economy-wide impacts.

S. No.	Reason for improved transport efficiency	Basis	Plasterboard case study		Economy-wide impacts	
			Impact parameters			
			Vehicle-km	Fuel- (litres)	Vehicle-km	Fuel (litres)
1.	Adoption of DTS model	30% reduced vehicle-km	126,100		7,392,000	-
2.	LP-based reduction in truck trips	38% reduced vehicle-km	207,600		6,550,000	-
3.	Integration of reverse logistics	9.4% improved capacity utilisation	-	19,674	-	-
4.	LP-based improved capacity utilisation	21% improved capacity utilisation	-	35,500	-	1,095,000

From the results in Table 10, and application of individual or cumulative impacts of reduction in vehicle-km and fuel consumption, the annual monetised benefits for plasterboard distribution and its economy-wide extrapolation is shown in Table 11.

Table 11. Comparison of improved efficiencies (km).

S. No.	Type of Costs	Plasterboard distribution (million NZ$)	Economy-wide (million NZ$)
1.	Direct (O&O)	1.31	52.27
2.	Indirect (External)	1.38	47.42

While in the case of plasterboard distribution, the reduction in direct costs is lower than the indirect costs, in the case of the economy-wide impacts, this reverses. This can be explained by the contribution of fuel savings to vehicle-km in the two cases and the per-litre contribution of fuel to emissions being higher than that per vehicle-km by an order of 4. While in the case of the plasterboard case study, the fuel reduction contributes more than 50% of the total vehicle-km reduction, in the case of the economy-wide impact, it is only circa 17%.

From the literature, vertical integration of business processes is considered an instrument for improving system efficiencies (Barreyre, 1988; Guan & Rehme, 2012). At the same time, a general dearth of SC oriented logistics data prevents evidence-based quantification of freight logistics efficiency improvement (McKinnon, 2015). The present analysis of operational transport data and quantification of transport efficiencies achieved from integration (downstream SC – integrated distribution, upstream SC – integrated planning between transport supplier and consumer, and lateral SC – waste management as a separate, however, dependent business) bridges this gap. It validates applicability of business process integration outcomes, i.e., improved logistics efficiency, to the CSC.

Embodiment of carbon into construction materials and built assets is a significant domain impacting circularity of the construction industry. Improvement in efficiencies (reduced vehicle-km and fuel consumption) points to evidence-based evaluation of this aspect, and, therefore, the shift towards circularity. Similar benefits are also likely to accrue from waste being used as raw material for further manufacture, and therefore, present themselves for a similar analysis.

8. Conclusion

The extensive and interdisciplinary nature of the CSC makes it prone to inefficiencies at the intersection of different domains or segments. Transport operations are inherently fragmented, with a transport component intrinsic to every construction site, but asset ownership and deployment typically externalised. Transport costs can be anywhere up to two-thirds of logistics costs. Differentiated materials delivery and waste removal further disaggregate the already fragmented CSC. Inefficiencies from the insularity of the planning process across segmental boundaries aggregate incrementally to a substantial degree, with impacts visible at the macro level.

Quantifying inefficiencies, specifically those pertaining to transport operations, is constrained by a general dearth of pertinent data. Typically, available transportation data relates to individual freight journeys with a general lack of an SC perspective. Material costs being based on a straight take-off of required quantities, with all associated costs consolidated into the material cost, makes differentiating logistics costs near impossible. In turn, this presents barriers to quantifying optimisation from implemented SC models, and assessment of further potential for efficiency enhancement.

Construction logistics are managed typically from the contractor's perspective. This tends to disaggregate operations rather than integrating them. Viewing transportation from the supplier's viewpoint turns the perspective around by providing a means to consolidate deliveries, and therefore, improve resource utilisation.

This paper has analysed operational transport data pertaining to plasterboards distribution within Auckland. The distribution model has re-configured activities, re-combined resources, and re-positioned involved actors through vertical integration of the distribution function, and outsourcing transport on a 2PL basis. Termed the DTS model, the analysis indicates an improvement in transport efficiency over BAU (FIS model). Application of LP from the operations research domain, and integration of reverse logistics further indicate the potential for substantial efficiency improvements. The analysis evidences integrated planning between the supplier (manufacturer), the LSP (transport contractor), the client (BM), and the end-user (construction site) as an effective tool for improving process efficiencies. Integrated planning leads to approximately 22% improvement in transport capacity utilisation, and integration of reverse logistics another circa 9%. Monetisation of sustainability impacts from improved efficiencies have been reckoned using benchmarks from domestic and international research. These work out to approximately NZ$1.31 million in direct costs and NZ$1.38 million in indirect costs annually.

The benchmarks and outcomes from the specific case study were then applied to the wider NZ residential construction sector, specifically to the manufactured construction products segment. Non-availability of country-wide transport data (distances, loads, vehicle capacities) and waste arisings pertaining to the specific CSC segment precluded analysis of potential improvements based on integration of reverse logistics. An estimated annual benefit of approximately NZ$52.27 million in direct (O&O) costs NZ$47.42 million in external costs per annum has been reckoned from improved transport sustainability outcomes. Though the figures may be indicative as a result of the benchmarks being inferred from a case study and information obtained from a wide variety of published documents, the analysis definitely points to the potential for efficiency improvements and the associated monetisation of sustainability outcomes.

The overall analysis and assessment of benefits also point towards the research direction of transport efficiencies and waste management as determinants of embodiment of resources in construction materials, and therefore, as enablers of the shift towards circularity.

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Conflict of interests

All the authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

Author contributions

Conceptualization: Kamal Dhawan, John E. Tookey; Investigation: Kamal Dhawan, John E. Tookey, Mani Poshdar; Methodology: John E. Tookey, Ali GhaffarianHoseini; Analysis: Kamal Dhawan, Mani Poshdar; Writing – original draft: Kamal Dhawan, Mani Poshdar; Writing – review & editing: John E. Tookey, Ali GhaffarianHoseini.

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