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LEAN CONSTRUCTION SUPPLY CHAIN: A TRANSPORT PERSPECTIVE

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ABSTRACT

The extensive and interdisciplinary construction supply chain is susceptible to inefficiencies at the interfaces of organisations. These inefficiencies are exacerbated by intricate logistics systems that operate among numerous stakeholders and actors, involving concurrent activities, processes, and on- and off-site systems. Transportation stands out as the most significant element within construction logistics. The fragmentation of the transport function stems from its intrinsic nature to every business, typically involving externalised asset ownership and deployment. Inefficiencies infiltrate the system due to isolated planning across different segments, gradually accumulating into macro-level visibility.

To optimise logistics, particularly the transport function, identified strategies involve reconfiguring activities, combining resources, and repositioning actors. This paper delves into the impact of vertically integrating distribution, implementing integrated planning for transport operations, and incorporating reverse logistics into operations on the transport function within a supply chain for manufactured construction products. The study evaluates sustainability impacts using transport efficiency metrics and domestically determined parameters to benchmark the 'leaning and greening' of the specific supply chain under consideration.

KEYWORDS

Construction transport, Construction logistics, Optimised transport, Lean construction supply chain.

INTRODUCTION

The construction sector, as a norm, makes up around 13% of the global Gross Domestic Product (GDP) (UNEP, 2020). This industry holds a crucial position in fostering job opportunities, advancing infrastructure, and supporting businesses, thereby contributing significantly to socio-economic progress. Despite its beneficial influence, construction is a noteworthy consumer of resources and a substantial emitter of carbon. Worldwide, it is responsible for about 36% of energy consumption and 39% of emissions (UNEP, 2020).

A typical construction project involves the amalgamation of numerous resources and materials sourced from various suppliers, resulting in a complex and distinctive end-product (Guerlain et al., 2019; Tetik et al., 2021). Logistics, encompassing transportation, warehousing, and inventory management, represents a crucial interdisciplinary aspect of construction supply chains (CSC). It exerts a significant impact on project management and costs (Ying & Tookey, 2014). In a fragmented supply chain (SC), inefficiencies in coordination and integration become

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apparent at organizational and operational boundaries (Alashwal & Fong, 2015). The subsequent increase in logistics process overheads gives rise to sustainability concerns.

Construction logistics undertake two primary roles: overseeing on-site logistics activities and facilitating the transportation of resources to and from construction sites (Ghanem et al., 2018). Approximately 60-80% of the total work conducted on a construction site revolves around the acquisition of materials and services (Sezer & Fredriksson, 2021). The intricacy of construction logistics arises from the adoption of customised procurement methodologies by the relevant stakeholders, coupled with the fragmented nature of the SC (Tetik et al., 2021).

Transportation constitutes the most substantial element of logistics, as most other logistics processes, other than warehousing, are categorised as business processes rather than physical ones (Szymonik, 2012). The characteristic of construction materials being of low value but high volume (Balm & van Amstel, 2018) can result in significant transportation needs, even for relatively modest projects. Consequently, transportation holds considerable importance in the realm of construction logistics.

Apart from energy consumption, emissions, and financial costs, transport comes with inherent externalities. These externalities may manifest directly, such as noise, air pollution, and congestion, or indirectly, e.g., disruptions in ecosystems, health impacts, and reduced quality of life (Chatziioannou et al., 2020). Issues related to transport in construction arise both within the construction site and beyond it, influenced by factors such as (Fredriksson et al., 2020):

- SC inefficiency, where lack of information and coordination leads to low delivery performance.
- Inefficiency of on-site logistics, leading to avoidable loss of resources, and therefore, higher inputs for maintaining delivery performance.
- Disjointed management of the construction site and the associated SC, with a distinct boundary between the two.

Given the projection that transport is expected to account for approximately 60% of global emissions by 2050 (Edenhofer, 2015), the diverse array of resulting impacts suggests the potential for enhanced sustainability outcomes through optimisation. In the construction industry, in particular, the primary rationale for pursuing optimisation is the improvement of workflow reliability (Perez et al., 2015; Tetik et al., 2021).

Every business inherently involves transportation, with asset ownership and deployment typically being outsourced. Consequently, from an SC standpoint, both strategic instruments and operational mechanisms serve as effective tools for optimising transport (Dhawan et al., 2022). However, the ability to make evidence-based decisions in the freight/logistics domain is hindered by a lack of pertinent data, as the available data usually pertains to individual journeys and lacks a comprehensive SC perspective (McKinnon, 2015).

In the context of New Zealand (NZ), approximately 93% of freight transportation relies on roads, with construction accounting for over 30% of this activity (Ministry of Transport New Zealand Government, 2020). The average truck's Gross Vehicle Mass (GVM) stands at around 22,500 kg (Wang et al., 2019), yet the average payload carried is only about 9.64 tonnes (Ernst & Young, 2021). These industry-wide figures, relevant to construction transport as well, underscore the immediate need and potential for optimising transportation, leading to improved sustainability.

The identified research gap pertains to using logistics planning as a means to achieve optimisation of transport at the strategic as well as operational levels. This study delves into the effectiveness of vertically integrated distribution, integrated transportation planning, and the integration of forward and reverse logistics as strategies to enhance efficiency and sustainability within a specific segment of the NZ CSC. The findings of this study indicate the potential applicability of these strategies across the broader spectrum of the CSC.

ANALYSIS BASELINES

The analysis baseline for this paper evolves along four directions: -

1. The problem of construction logistics.
2. A review of the construction materials SC.
3. Metrics for evaluating freight transport efficiency.
4. The resulting research questions.

THE CONSTRUCTION LOGISTICS PROBLEM

Construction logistics coordinate, control, and manage material flow from processing of raw material to final use in the construction process. Additionally, they include waste removal and disposal along the reverse route (Ying & Tookey, 2014). Stakeholders participate in various on- and off-site activities, which may be in the domains of planning/organising, transport, and activities related to construction on site (Janné, 2020). Key concerns include planning, designated spaces for loading/unloading, materials handling, storage, and linking actors and channels of the logistics system through transport (Janné & Fredriksson, 2019; Lange & Schilling, 2015).

The conventional perspective on construction logistics primarily centers around the main contractor's viewpoint, aiming to enhance on-site production efficiencies (Fredriksson et al., 2022). The management of suppliers and on-site deliveries is guided by the primary constraint of storage space (Lundesjö, 2015). The main contractor can effectively tackle both horizontal fragmentation issues (involving disaggregated skill sets/expertise) and vertical fragmentation issues (related to well-defined phases) due to the project-centric nature of construction delivery. However, concerns related to longitudinal fragmentation are overlooked, as suppliers and transporters operate independently and only collaborate for site-specific deliveries. The following major reasons for the differences between freight transport and construction transport (optimisation) are, therefore, inferred: -

- The distinctive characteristics of the CSC, marked by bespoke operations and a fragmented composition (Alashwal & Fong, 2015; Guerlain et al., 2019).
- Patterns of transport usage driven by project-centric delivery requirements (Sezer & Fredriksson, 2021).
- The widespread use of industry-specific equipment (Guerlain et al., 2019).
- Unlike city logistics, where responsibility lies with city managers, the construction industry bears the responsibility for construction logistics management (Janné & Fredriksson, 2021).

From the suppliers' standpoint, the fragmented logistics perspective undergoes a reversal. Deliveries managed by suppliers become effectively consolidated, showcasing greater efficiencies in comparison to the typical business-as-usual (BAU) approach (Dhawan, 2023).

THE CONSTRUCTION MATERIALS SUPPLY CHAIN

The construction materials SC is composed of three primary actors. The bulk suppliers and the construction site represent the two ends. The Builders' Merchants (BMs) and retailers are interposed between the two. The interposed actors provide interim storage and consolidation. The typical methodologies adopted for construction materials supply are illustrated in Table 1 (Commerce Commission New Zealand, 2022).

In the CSC, BMs play a crucial role as the primary economic stabilisers. They extend lines of credit to contractors and absorb market fluctuations by holding 'safety' stocks. BMs' inventory carrying costs can reach up to a fifth of the overall inventory costs (Vidalakis et al., 2011).

Table 1: Construction materials supply models (Commerce Commission New Zealand, 2022)

Model	Description	Typical supplies
Freight into Store (FIS)	Routing of bulk or retail quantities of materials through BMs, where bulk suppliers cannot manage retail quantities.	Aggregate, bricks, cement, fittings, plumbing, fixtures, heating supplies, tools
Specialist stockist sales	Marketing by manufacturers through their own subsidiaries.	Proprietary items
Direct to Site (DTS)	Material supplied directly at the construction site by the bulk supplier, where intermediaries are not required.	Steel framing

BMs operate nationally, regionally, and locally. Customer interaction invariably takes place through area specific depots, whose transport is driven by customer delivery demands. A small vehicle fleet caters to local customers. Delivery planning relies on staff knowledge of the local area layout (Dhawan, 2023).

Regional and national merchants centrally oversee their vehicle fleets, typically under the management of a transport professional. However, in the case of local BMs, the depot manager, who may lack transport expertise, is responsible for fleet management, prioritising customer service over transport efficiency. The order cycle is typically 24 hours, catering to the next day's tasks (Commerce Commission New Zealand, 2022). Inefficiencies are concealed within the seamless quantity take-off, representing ‘hidden costs’ of construction material (Balm & Ploos van Amstel, 2018; Verlinde, 2015; Ying & Tookey, 2014).

FREIGHT TRANSPORT EFFICIENCY METRICS

Freight transport system efficiency is a strategic measure of goods handling, whereas vehicle efficiency is operational/tactical (Pahlén & Börjesson, 2012). Vehicle efficiency revolves around 'filling rate,' - the ratio of actual loads transported to the maximum achievable with vehicles consistently loaded to their rated capacity (McKinnon, 1999). For trucks, vehicle efficiency - the ratio of utilised and available capacities - is expressed by five individual measures (McKinnon, 2010; Pahlén & Börjesson, 2012):

- **Level of empty running** Percentage of the distance travelled empty.
- **Weight-based loading factor** Ratio of the actual weight carried to the rated payload capacity.
- **Tonne-km loading factor** Ratio of the actual tonne-km (product of weight and distance) to the rated payload capacity-based tonne-km.
- **Volumetric loading factor** Percentage of the total vehicle cubic capacity occupied by the load.
- **Deck-area coverage** Percentage of the floor area of the vehicle covered by a load.

Measuring vehicle efficiency includes both onward and return trips. The construction sector faces difficulties in securing loads for return transport, turning what was once deemed empty running waste (Bølviken et al., 2014) into consideration through the sustainability lens (Kohn & Brodin, 2008). As a result, both policy and business perspectives prioritise minimising empty running in the pursuit of sustainable distribution strategies (McKinnon & Ge, 2006).

PROBLEM DESCRIPTION, DATA, AND RESEARCH QUESTIONS

The absence of pertinent data hampers evidence-based decision-making in the field of construction freight and logistics. The currently accessible data tends to focus on individual freight journeys without providing a comprehensive SC perspective (McKinnon, 2015). This poses a challenge when attempting to quantify efficiency improvements and analyse the potential for further enhancement resulting from implemented SC models and operational philosophies.

PROBLEM DESCRIPTION

The focus of the investigation is plasterboard supply in Auckland, NZ. The BAU scenario uses the FIS model for distribution through a disaggregated network having three key nodes: the manufacturing facility warehouse, BM establishments, and construction sites. Two links connect these nodes for both information and material flow (Bulk supplier – BM and BM – Construction Site), each emphasising storage as a primary function. This model aligns with the theoretical ‘Distributor storage with carrier delivery' logistics model (Chopra et al., 2013).

The modified (DTS) model integrates distribution and manufacturing vertically, outsourcing transport through second-party logistics (2PL). In contrast to the FIS model, this configuration includes three nodes and three links. Two of these are information links for invoicing and delivery (Contractor – BM, BM – Bulk Supplier), while the third (Bulk Supplier – Site) manages physical delivery. The manufacturer directly delivers materials invoiced by the BM to the site, exemplifying the 'Manufacturer storage with direct shipping' logistics model (Chopra et al., 2013).

DATA AVAILABILITY

This study examines three months’ truck movements data (October 2020 to December 2020) related to plasterboard delivery using the DTS model in Auckland, NZ. The data was obtained from the logistics department of NZ’s largest plasterboard manufacturer and supplier, who maintain a log of daily truck movements for plasterboard delivery. The dataset was obtained in two parts. The first part provided the details of trucks used for plasterboard delivery (i.e., manufacturer, model, rated payload, and Gross Vehicle Mass - GVM). The second part provided details of trips undertaken by these trucks daily for plasterboard delivery (i.e., truck ID, departure time, quantities of items in accounting units and weights, and delivery destinations for various consignments). The data pertained to 2762 trips across 58 days. Travel distances and drop sequences were, however, not available in the dataset. The following operational characteristics emerged from the dataset: -

- 26 trips with different rated payload undertaking 42 trips transporting an average of 330 tonnes of plasterboard daily.
- One to six drops associated with each truck trip.
- More than three drops were seen in less than 1% of the trips, hence ignored, being insignificant for analysis.
- Almost 75% of the trips were single-drop trips.
- Transport was procured on a per-tonne basis irrespective of distances involved.
- Diesel-powered flat-bed trucks comprising the fleet.

RESEARCH GAP AND QUESTIONS

The DTS solution appears to have provided greater service efficiency and customer satisfaction vis-à-vis the FIS model. However, improved transport efficiency has not been quantified. In the Lean philosophy context, this research gap prompted the following research questions: -

- **RQ1.** What is the improvement in transport efficiency in DTS deliveries compared to FIS deliveries.
- **RQ2.** What is the potential for further transport efficiency improvement and the potential means to achieve it?
- **RQ3.** What are the means available to integrate reverse logistics and what are the likely impacts of this integration on transporting efficiency?
- **RQ4.** How does the supply chain become Leaner as a result of the above?

TRANSPORT EFFICIENCY ANALYSIS

MEASURES SELECTED

The analysis focused on weight-based and tonne-km-based efficiencies, termed 'loading efficiency' and 'capacity utilisation,' respectively. Loading efficiency (static), is measured at dispatch, and does not consider transportation distance. Capacity utilisation (dynamic) factors both loads and distances. To introduce distances and drop sequences, 370 trips were selected as a statistically significant sample representative of the dataset (2762 trips), using random (probability) sampling (Krejcie & Morgan, 1970).

QUANTIFYING EFFICIENCY IMPROVEMENT OF DTS OVER FIS MODEL

Through vertical integration, the DTS model reduces one node and one link in the distribution transport network (Figure 2).

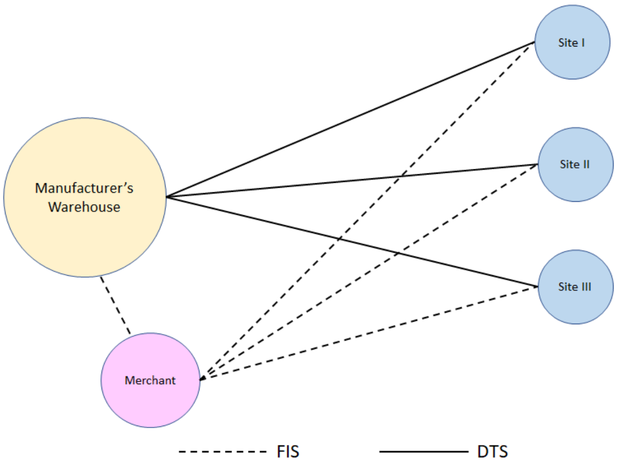

Figure 1: Transport network configurations for the DTS and FIS distribution models

Given that the three nodes connected by links form a triangle, any one link would always be shorter than the sum of the other two, unless all three are collinear – highly improbable in an urban setting. To estimate efficiency improvement through DTS rather than FIS deliveries each BM-destination pairing, the reduction in travelled distances served as a straightforward assessment parameter. A majority of the truck trips being single-drop (circa 75%) permitted considering individual BM-destination distances for the analysis. Inter-node distances were obtained from Google Maps. The analysis revealed a 30% reduction in distances travelled, equivalent to 11.1 km per trip, between the DTS and FIS models.

POTENTIAL FOR FURTHER EFFICIENCY IMPROVEMENT

The drop sequence was incorporated into the data sample (370 trips) from the 'Eroad' database (a NZ IT company providing GPS-enabled tracking services). Utilising inter-node distances, sequence of drops, loading efficiency, and individual destination loads, the analysis focused on tonne-km based capacity utilisation (Table 2).

The findings revealed a daily underutilisation of approximately 252 tonnes of truck payload, leading to non-utilisation of 72% tonne-km available. This highlights the necessity for enhanced planning strategies to decrease the number of daily truck trips while maintaining delivery output.

Table 2: Loading efficiency and capacity utilisation of trucks (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

APPLICATION OF OPERATIONS RESEARCH

Transportation Problem

Logistics incorporates strategies and tools from various fields (Hrablik et al., 2015). In this case, the Transportation Model from operations research was explored as an optimisation tool. It typically involves a network with nodes representing sources and destinations connected by arcs representing routes, material quantities, and per unit shipping costs, with the objective of minimising costs while meeting destination requirements within the origins' supply capacity (Taha, 2013). The problem could not be transformed into a classical transportation problem due to a single origin and uniform channel costs. It was, therefore, reformulated as follows: -

- The sample dataset was disaggregated into daily operations' sub-datasets.
- The rated payload of each truck was considered an individual source (supply).
- Each delivery was considered an individual consumer (demand).
- The channel cost, being fixed, was considered unity.

The transportation problem was solved using MSExcel, which presented an upper limit of 200 objective co-efficients in the problem matrix. Being 'proof-of-concept' exercise, a truncated daily trip dataset while maintaining trip integrity, was used. The solution (decision variables - allocation of loads to trucks) are 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	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 application of Linear Programming (LP) optimised the initial (truncated) 11 trips to 7. Extrapolating this to the actual baseline of 42 trips results in a daily reduction of 16 trips, without impacting delivery.

The Need for Integrated Planning

The application of LP highlighted the necessity for integrated planning between the transport contractor (supplier) and the bulk supplier/manufacturer of plasterboard (consumer). Currently, the manufacturer's priority is the daily transportation of ordered plasterboard quantities. The quantity of trucks employed, or the distances covered is not a consideration, given the 'per-tonne' pricing model. The transport contractor has the discretion of resource allocation. No resource-use analysis was considered essential as long as the daily tonnages are delivered.

Optimising transport becomes a necessity in two scenarios: when payments are distance-based (per-km) and when sustainability is integrated into the operational philosophy. The result is integrated planning, involving the manufacturer, even if only to monitor transport utilisation.

INTEGRATION OF REVERSE LOGISTICS

Truck capacity utilisation for a single-drop trip reaches a maximum of 50% (if fully loaded at the origin), and less than 50% for trips with more than one drop (Vrijhoef, 2015). Consecutive unloading at different drop points along the route creates capacity for backloads. This offers a potential opportunity to integrate reverse logistics with forward delivery, utilising waste backhauls on material delivery transport (Shakantu & Emuze, 2012). Considering estimates by Jacques (1999) and Nelson et al. (2022), approximately 20% plasterboard waste generation per site is considered a fair estimate.

Incorporating reverse logistics for removing plasterboard waste from construction sites relies on a comprehensive trip model, which includes the number of trips per truck site, load per trip segment, and the waste generated per site per truck. It considers average distances and loads from the sampled dataset, along with estimated plasterboard waste based on material delivery. Figure 2 illustrates the generalised trip model.

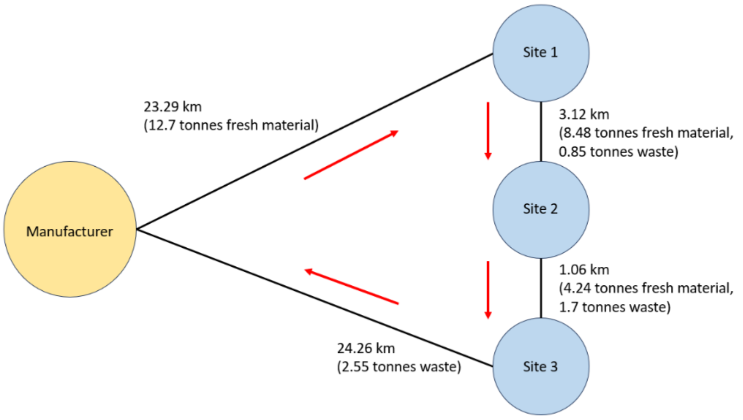

Figure 2: Generalised trip model

The incremental efficiency improvement utilises 326 tonne-km after LP application and 393 tonne-km with waste plasterboard backhauls, out of an available approximately 672 tonne-km per trip. This results in enhanced efficiencies of 49.38% and 58.04%, respectively, compared to the baseline of 27.61% (DTS).

LEANING THE SUPPLY CHAIN

THE LEAN PERSPECTIVE

The Lean perspective is discussed based on the three fundamental Lean construction principles, i.e., Respect for People, Continuous Improvement, and Maximising Value while Minimising Waste (Doan, 2022).

Philosophy 1: Respect for people

Respect for people extends to the environment. Thinking about the long-term environment, sustainability, and the impact of current actions on the planet and future generations (hidden stakeholders) forms an inseparable part of this philosophy (Doan, 2022). Table 3 brings out the reduction in vehicle-km and diesel consumption.

Table 3: Annual reduction in vehicle-km and fuel consumption

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

The impacts of these are reduction in emissions, pollution, carbon embodiment per-unit weight of plasterboard, noise, traffic congestion, disruption of ecosystems, negative health impacts from reduction of emissions due to optimised transport, and reduction in disposal to landfill and embodiment of resources due to re-cycling of waste plasterboard as raw material.

Philosophy 2: Continuous Improvement

Continuous improvement is illustrated by progressive application of tools and methodologies to scaffold improvements achieved. In the instant case, vertical integration, followed sequentially by application of operations research and integration of reverse logistics form the ‘improvement staircase’. The progressive transport efficiency improvement is shown in Figure 3.

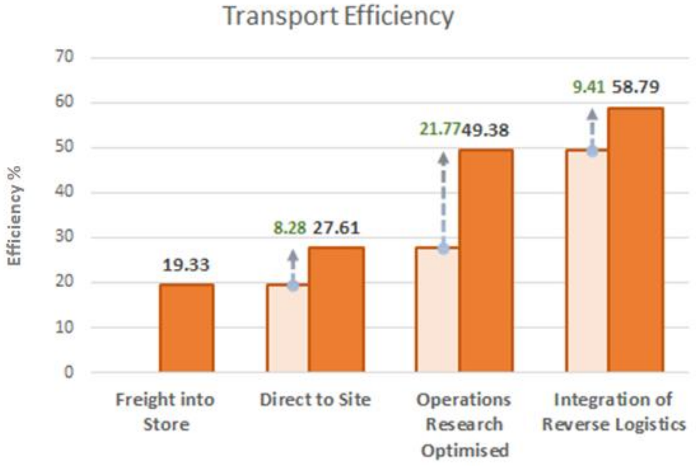

Figure 3: Progressive transport efficiency improvement

Philosophy 3: Maximising Value while Minimising Waste

Waste minimisation is achieved through i) Improved transport efficiency (reducing resource wastage); and ii) Utilisation of waste plasterboard as raw material for manufacture (Erbs et al., 2021) to the extent of approximately 10% to maintain quality, diverting it from landfill.

CONCLUSIONS

Logistics is multidisciplinary and does not have its ‘own’ tools and methodologies, adopting these from various domains. In answering the research questions, the initial analysis pertained to the quantification of transportation efficiencies achieved as a result of vertically integrating (Lidelöw & Simu, 2015) distribution with manufacture, from the Supply Chain Management domain. Next application of LP from the operations research/management domain was discussed as a tool for further optimisation. Integrated reverse logistics further improved transport efficiencies. The question of Leaning the SC was addressed by viewing the progressive improvement through the lens of fundamental Lean construction principles, i.e., Respect for People, Continuous Improvement, and Maximising Value while Minimising Waste.

The simple analysis leads to life cycle improvements in the SC, in addition to direct ones. It also points to further research directions such as quantification of reduced embodied resources, economic/cost implications of improved efficiency both within the CSC and economy-wide, issues of fleet management for improved operational sustainability, and the means for integrated planning.

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