

DECARBONIZING CONSTRUCTION THROUGH LOGISTICS: INSIGHTS FROM COLD CLIMATES

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ABSTRACT

Construction logistics and site operations are significant sources of emissions, especially in cold climates where heating, lighting, and equipment use are intensified. Design and early planning decisions determine material flows, site organization, and the duration of temporary energy-intensive systems. Although lean construction is known for reducing waste and variability, its potential to support emission-aware logistics planning is still under-explored. As a result, the links between logistics reliability, efficiency, and emissions remain unclear. This study investigates how design and production planning can be better aligned with low-emission strategies in cold climates. The study adopts an integrative qualitative review that synthesizes literature, certification and policy documents, and contextual material from Finland, Estonia and Canada. Findings show that design and production planning decisions influence construction phase emissions by shaping logistics system configuration, material flow reliability, transport intensity and duration of energy-intensive operations. These relationships are amplified in cold climate contexts where seasonal access constraints and energy demand increase emissions from logistics inefficiencies. Based on these, the study develops a framework that links improvements through lean in material flow and site coordination to systematic, emission aware planning. Results support researchers, policymakers, and practitioners in embedding emission-aware thinking into planning and logistics.

KEYWORDS

Logistics, design for logistics, lean construction, cold climate construction, sustainability.

INTRODUCTION

The construction sector is one of the most resource consuming and emission generating industries. The sector's emission footprint is expected to double globally by 2050 (Li et al., 2025). In addition to embodied materials and operational energy use, logistics activities and site operations contribute to greenhouse gas (GHG) emissions through material transport, handling, temporary energy use and on-site production. While embodied and operational emissions have received extensive attention, emissions arising during the construction phase remain

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underexamined (Weigert et al., 2022). This gap is particularly pronounced in Nordic countries where cold climates extend construction durations and increase temporary energy use and thus, emissions (Pikas et al., 2024). Despite growing attention to construction phase emissions, there is still limited understanding of how design and planning decisions propagate through production planning and logistics system configuration to shape these emissions.

Construction logistics practices such as logistics centers can significantly reduce the number of transports, thereby lowering emissions (Hamzeh et al., 2007; Sezer & Fredriksson, 2021). Prior work has shown that emissions from equipment are sensitive to planning and control decisions, particularly resource allocation and scheduling, as these choices affect operational efficiency and idling, and therefore emissions (Ahn & Lee, 2013). Yet, existing research on construction logistics mostly focuses on quantifying material transport emissions or comparing delivery modes (Girase et al., 2025). As a result, construction logistics is often examined in isolation from the design, execution and continuous improvement of construction production systems and from the upstream decisions that shape logistics requirements. Consequently, the relationship between design decisions, logistics system performance and construction phase emissions remains insufficiently articulated.

Although Life Cycle Assessment (LCA) define construction phase emission boundaries, it provides limited guidance on how production planning and logistics decisions can reduce these impacts. To address this gap, an integrative review examines how lean construction is discussed in relation to emission reduction, logistics efficiency, and site phase energy use; areas where lean's influence is often acknowledged but rarely analyzed. The review synthesizes academic literature, technical reports, standards, policy documents, and national strategies from Finland, Estonia, and Canada, including Finland's Climate 2035, the EU Green Deal, and Canada's Net-Zero Strategy, complemented by practice-based insights from the authors.

The findings are synthesized into a conceptual framework that articulates how design, lean principles and logistics system design can influence construction phase emissions. The analysis examines the role of climatic and regulatory contexts, identifies gaps in current certification and policy frameworks and outlines opportunities for embedding emission-aware thinking into project planning. By making **design–production planning–logistics–emissions** relationship explicit, this study contributes to lean by reframing design and production planning decisions as upstream determinants of construction phase emissions. The framework is intended to guide practitioners, policymakers, and researchers aiming to operationalize lean methods as emission mitigation strategies. The remainder of the paper proceeds with a background section on construction logistics and emissions, followed by a description of the research design. The findings are then presented, followed by discussion and conclusions.

CONCEPTUAL AND ANALYTICAL BACKGROUND

The reviewed background includes construction logistics, emissions and energy used during the construction phase, and common certification systems' treatment of logistics and sustainability.

CONSTRUCTION LOGISTICS, MATERIAL FLOW EFFICIENCY AND LEAN

Logistics play a crucial role in enhancing construction efficiency by influencing material management, labor productivity, and project outcomes (Dubois et al., 2019). In construction, the logistics responsibilities are often unclear, and processes vary widely between projects that contributes to delays and material handling inefficiencies (Andersson & Nilsson, 2018). Efficient material flow is essential for minimizing delays, reducing waste and improving labor productivity (Tetik et al., 2022). Logistics practices such as material kitting can stabilize assembly work, enhance workflow reliability and on-site productivity by minimizing time spent

searching for materials (Tetik et al., 2021). Moreover, centralizing materials at hubs can optimize material flows, reduce truck movements by 40% and lower costs (Guisson et al., 2023).

Improving construction material flow efficiency requires a comprehensive approach integrating advanced technologies and lean principles (Núñez-Merino et al., 2020). Linking production workflow with material supply, a core lean mechanism for stabilizing flow, reducing variability and waste, enables Just-in-Time (JIT) deliveries, reduces on-site inventories, and enhances demand reliability and overall value stream performance (Arbulu et al., 2005). Also, approaches such as vertically integrating distribution and coordinating transport planning can help streamline logistics operations (Dhawan et al., 2024). These strategies point to a growing industry movement toward industrialized and data-driven logistics systems.

Construction in remote locations lacks significant infrastructure, making transportation of materials, equipment, and personnel challenging. There is often a shortage of skilled labor and construction materials in remote areas, necessitating the mobilization of workforce and supplies from distant locations (Majumdar & Ruparathna, 2025). These increase the importance of early design and production planning decisions that can stabilize material flow. Finnish construction companies are increasingly adopting circular economy practices, such as reusing and circulating materials locally, which reduces transport needs and increases the importance of coordinated material flow. This approach emerged as a resilience strategy during the COVID-19 pandemic, highlighted the vulnerabilities in global supply chains (Piila & Sarja, 2024). These practices illustrate how early phase decisions can reshape logistics system configuration.

EMISSIONS AND ENERGY USE DURING THE CONSTRUCTION PHASE

Building Information Modelling (BIM) and LCA are used to automate data extraction and calculate embodied energy and emissions, considering production, transportation, wastage, and installation processes (Hong et al., 2014; H. Xu et al., 2025). LCA captures emissions across multiple transport stages, from raw material extraction to manufacturing and delivery to site. Both building and material-level LCAs demonstrate transportation as an integral component of life cycle emissions, with its significance increasing for longer transport distances (Barbhuiya & Das, 2023). This highlights that reducing transport demand through material efficiency, local sourcing and reuse represents a particularly effective emissions mitigation strategy. Yet, despite well-documented contribution of transport and on-site activities to construction phase emissions, recent research shows that construction phase emissions remain underrepresented or inconsistently reported (Vendel et al., 2026). Moreover, projects with better environmental ratings tend to generate fewer emissions from transport (Sezer & Fredriksson, 2021); yet, this reduction is not the result of explicit benchmarks for construction logistics within sustainability assessment systems, but rather a byproduct of broader sustainability-oriented project planning.

The condition characteristic of remote and northern regions amplifies the emissions consequences of logistics and production planning decisions. In Northern and remote regions, construction logistics are shaped by seasonal access limitations (Naumets et al., 2025). Projects rely on a seasonal window for transporting heavy materials and equipment, while off-season access relies on less flexible or more emission-intensive options and risk of delays and prolonged site operations, which can significantly increase temporary energy use and logistics emissions in cold climates. The high transportation needs due to the disperse geography and economic structure result in significant energy consumption and emissions that poses a challenge for sustainable development (Imppola, 2016). Moreover, winter roads enable transport to, from, and within isolated areas that lack permanent all weather road access (Lightstone et al., 2021) introducing additional variability into material delivery timing and reliability. As a result, unstable material flow and extended construction durations can increase resource consumption and logistics emissions in cold climates.

Prefabrication offers several advantages for construction in remote areas such as the Nordics and Canada. Prefabrication helps address the specific challenges of these regions by shifting component production to controlled environments and transporting them to site for assembly, thereby reducing on-site construction time and limiting weather related delays (Samimi & Safiuddin, 2019). As a design phase decision, prefabrication reshapes logistics and production planning and can reduce construction phase energy use and emissions. Thus, the controlled manufacturing environment allows for better management of emissions and energy use, contributing to lower overall emissions (Cheng et al., 2023).

CERTIFICATIONS, REGIONAL STRATEGIES AND THEIR TREATMENT OF LOGISTICS EMISSIONS

The European Union's (EU) growing emphasis on circular economy strategies stresses efficient material flow, reuse and waste minimization (Directive 2018/844/EU, 2018). Emerging circular construction practices, such as local reuse and circulation of materials, are reshaping design, production planning and logistics requirements (Ericsson et al., 2024) which reinforce the need for coordinated and emission-aware construction logistics systems. Recent Finnish Building Information Foundation guide on determining the suitability and applicability of reusable construction products, and their design demonstrates the complexity of managing material flows (Building Information Foundation RTS, 2025); tasks that require coordinated, transparent and predictable site logistics which are fundamentally lean challenges. A similar pattern can be seen in Canada, where decarbonization efforts mainly focus on low-emission materials, building performance, and life cycle impacts, while the influence of design phase decisions on construction phase material flows and site logistics is addressed far less explicitly (National Research Council Canada, 2023).

Current sustainability assessment systems such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Level(s) and standard LCA frameworks primarily focus on defining environmental performance outcomes rather than prescribing how construction activities should be planned or executed. As a result, while these frameworks capture construction phase emissions at a reporting level, they provide limited process-level guidance on logistics practices, on-site material flow or lean methods, and do not explicitly address the underlying processes that generate the emissions. Consequently, logistics emission reduction opportunities are not consistently made visible within current approaches.

Level(s) defines sustainability performance via LCA, life cycle cost and indoor air quality, and promotes life cycle thinking, yet its core indicators do not include metrics for on-site material flow, delivery scheduling, JIT or logistics processes (Dodd et al., 2021). It treats construction phase emissions such as energy and waste generically and lacks requirements for logistics and flow optimization.

BREEAM International New Construction Version 7 does not include explicit credits or assessment criteria targeting logistics system design, such as JIT delivery strategies, material kitting, consolidation centers or other logistics choices (BREEAM, 2025). BRE Practical Note 326: Methodology for LCA of buildings using EN 15978:2011 European Standard confirms that contemporary LCA frameworks treat the construction phase primarily as a resource and activity accounting exercise, focusing on transport distances, vehicle types, installation energy, water use and waste generation, without evaluating the organization or performance of logistics systems. It documents A4 and A5 exclusively in terms of transport distances, vehicle types, installation energy, water and waste, without any assessment of delivery precision, material flow and JIT coordination (BRE Global, 2018).

Across BREEAM, LEED and standard LCA frameworks (EN 15978; ISO 21930), indicators or credits addressing construction logistics, on-site material flow, delivery precision,

JIT, material kitting, or other lean logistics methods are not explicitly addressed. BREEAM only requires limited data collection on transport and LEED's requirements focus on minimizing disturbance rather than optimizing logistics (Sezer & Fredriksson, 2021).

Zero Carbon Building Standard (ZCB) aims for net-zero carbon balance over a building's life cycle (Canada Green Building Council, 2024). It captures embodied and operational carbon broadly, yet it lacks process level scrutiny or incentives for logistics or flow practices. As with other international LEED applications, LEED Canada treats sustainability at the building design and operation level, not construction logistics or site flow ('LEED', n.d.).

The manufacturing industry has a more established basis for quantifying and managing logistics emissions through dedicated calculation frameworks and standards such as EN 16258 and ISO 14083 (Wild, 2021). Manufacturing research and practice more explicitly link emissions reduction to upstream design choices and integrated production planning, including scheduling integration and digital/AI tools for emissions aware decisions (B. Xu & Qu, 2022).

Across the literature streams, three consistent themes emerge. First, design and production planning decisions shape logistics system configuration and material flow reliability. Second, logistics system performance influences construction phase emissions through transport intensity, handling requirements, site duration and temporary energy use. Third, certification and reporting frameworks recognize construction phase emissions, but provide limited process-level guidance on how design and logistics decisions can be used to mitigate them.

METHOD

This study adopts a qualitative, multi-method research design that draws on empirical project materials, policy frameworks, certification systems and site documentation from Finland, Estonia and Canada. An integrative literature analysis (Torraco, 2005) was used to synthesize and interpret findings across fragmented research streams on lean construction methods, construction logistics and site emissions as analytical input to identify recurring relationships between production planning, logistics system configuration and construction phase emissions. The selection of the countries is motivated by their shared cold climate conditions and their differing regulatory and logistics contexts. These countries represent different levels of lean maturity, distinct supply chain structures and sustainability requirements that allow the research to identify robust patterns and context specific barriers.

The research design is structured around complementary data sources as a literature review on lean construction, construction phase emissions and used to identify mechanisms linking design decisions, production planning and logistics with emissions outcomes; analysis of national and international sustainability certification systems including LEED, BREEAM, the EU Level(s) framework, ZCB and LCA methodologies such as EN 15978, ISO 21930, the Dutch National Environmental Database (NMD NL), and BRE PN326) used to examine how construction phase emissions and logistics-related processes are currently represented; review of project documentation and publicly available emission reports from each country, including logistics plans and temporary energy data when accessible, used to contextualize observed patterns; and contextual insights from the co-authors, used to interpret findings and identified relationships. Figure 1 illustrates the research design.

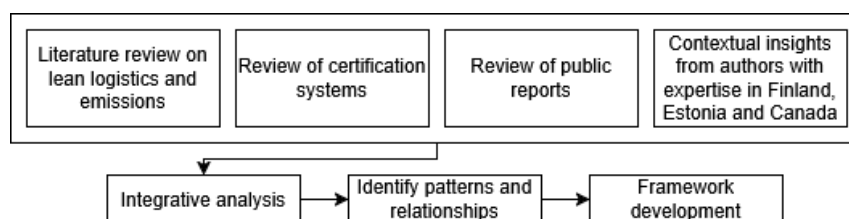


Figure 1: Research design

The analytical process consisted of three stages: (1) reviewing and extracting relevant insights from the four data sources; (2) iteratively comparing and mapping relationships between design decisions, production planning, logistics system configuration and construction phase emissions; and (3) synthesizing these relationships into a conceptual framework. This process enabled the study to identify causal linkages between upstream decisions and emissions outcomes during construction, particularly under cold climate conditions.

FINDINGS

LOGISTICS CHALLENGES IN COLD CLIMATE CONSTRUCTION

The analysis indicates that construction logistics is often fragmented and inconsistently coordinated, resulting in avoidable delays, material handling waste and workflow interruptions (Andersson & Nilsson, 2018). These stem partly from unclear responsibilities and partly from the widespread reliance on decentralized or reactive logistics arrangements, even though more integrated and supply network-coordinated models demonstrate significantly higher efficiency (Dubois et al., 2019).

The analysis shows that where design and production planning enable structured logistics practices such as kitting, centralized hubs or coordinated planning, material flow becomes more predictable, reducing disruption frequency and transport needs (Guisson et al., 2023; Tetik et al., 2019). Studies highlight good potential reductions in vehicle movements and logistics costs, yet such practices are not consistently adopted (Dhawan et al., 2024; Guisson et al., 2023). Although the reviewed sources do not explicitly focus on cold climates, the identified logistics issues such as rehandling, delays and unstable flow amplifies implications in colder regions where longer installation times and operations sensitive to weather increase temporary energy use and machinery activity related to lifting, material handling and site operations (Lightstone et al., 2021; Naumets et al., 2022).

In Estonia, the longer project durations associated with cold climatic conditions correlate with higher GHG emissions from site operations, as extended construction periods increase the use of temporary energy, machinery and on-site resources (Pikas et al., 2024). Recent digitalization efforts, such as the adoption of digital waybills, enable real-time tracking of load weights and fuel consumption, enabling real-time monitoring of loads and transport activity, thereby improving transparency of logistics performance and exposing inefficiencies such as empty return trips that contribute to avoidable A4 emissions (Tõnts et al., 2026).

Finland experiences seasonal variations, particularly harsh winters, which impact transport infrastructure. For example, the variability in winter weather conditions, including the decline in winter sea ice cover, affects maritime transport and necessitates robust infrastructure to handle these changes (Altarriba, 2025). The design of transport infrastructure places a strong emphasis on minimizing environmental impact. The findings identify logistics coordination as a measurable decarbonization mechanism rather than a marginal efficiency improvement. A prominent example is the City of Helsinki's systematic coordination of excavated soil reuse across construction sites, which has substantially reduced transport demand, fuel consumption and emissions. By the end of 2019, this mass coordination approach had resulted in cumulative savings of 17,100 tons of CO₂, demonstrating how logistics system design directly influences construction phase emissions (City of Helsinki, 2020).

The Canadian findings highlight a distinct cold climate logistics typology shaped by extreme distances and reliance on seasonal winter road infrastructure. Remote construction frequently depends on winter roads that require sufficient freezing degree days (FDDs) to support heavy transport. Reductions in freezing conditions have shortened winter road operating seasons and increased infrastructure failure risks, undermining the reliability of road-freight logistics networks (Barrette et al., 2022). Research on Canada's winter road network

shows that these systems are highly sensitive to climate warming because they depend on sufficiently cold periods to form and remain operational (Stockton et al., 2021). Such vulnerabilities have implications for logistics reliability, freight accessibility and the cost and complexity of materials transport in cold regions, with broader effects on on-site construction timelines and temporary energy use.

OPPORTUNITIES TO ALIGN LEAN METHODS WITH LOW EMISSION LOGISTICS

The analysis of sustainability assessment systems reveals that, while environmental performance reporting and LCA are required across design, construction and operational phases, no system includes explicit credits or requirements for logistics process design or lean delivery strategies. As a result, while construction phase emissions and transport impacts may be reported through LCA modules, the underlying logistics processes that generate these emissions are not directly incentivized or assessed. This process blind spot means efficient logistics practices and flow improvements are neither required nor rewarded in current frameworks.

A significant opportunity emerges from the misalignment between what certifications measure and the processes that drive those measurements. Lean's emphasis on flow, reliability and waste minimization directly aligns with logistics strategies' sustainability. The findings therefore suggest that lean methods could serve as practical pathways for reducing logistics emissions, particularly if integrated more explicitly into sustainability assessment and production planning. Table 1 summarizes the key findings.

Table 1: Key findings, supporting evidence, and correspondence to framework domains

Key findings	Supporting evidence	Implication for framework
Fragmented and reactive logistics arrangements cause delays, rehandling, and workflow interruption	(Andersson & Nilsson, 2018; Dubois et al., 2019)	Production planning and flow reliability. Logistics system design
Structured practices such as kitting, centralized hubs, and coordinated planning improve material flow predictability and reduce transport needs	(Dhawan et al., 2024; Guisson et al., 2023; Tetik et al., 2019)	Logistics system design
Cold climate and remote conditions amplify the emissions consequences of unstable flow through longer durations, temporary energy use, unreliable access	(Barrette et al., 2022; Lightstone et al., 2021; Naumets et al., 2022)	Climate and regulatory context
Coordinated logistics and digital visibility can function as decarbonization mechanisms by reducing transport demand and exposing inefficiencies	(City of Helsinki, 2020; Pikas et al., 2024; Tönts et al., 2026)	Logistics system design
Certification and LCA report impacts, but do not explicitly assess logistics process design or lean delivery practices.	(BRE Global, 2018; BREEAM, 2025; Sezer & Fredriksson, 2021)	Climate and regulatory context

Building on the findings summarized in Table 2, the synthesis and contextual insights reveal that construction phase emissions are shaped by three interacting explanatory domains: (1)

upstream design and production planning, (2) logistics system design, and (3) climatic and regulatory context, which together influence flow reliability, site operations and ultimately construction phase emissions. Existing methodologies and certification systems primarily define expectations, limits and reporting requirements for environmental outcomes rather than prescribing how production planning or logistics systems should be designed. Thus, production planning, logistics system design and contextual conditions are addressed separately, even though their interactions determine the emission intensity of operations. The proposed framework in Figure 2 integrates these domains to explain how lean principles can influence logistics emissions and site phase energy use, particularly in cold climate regions.

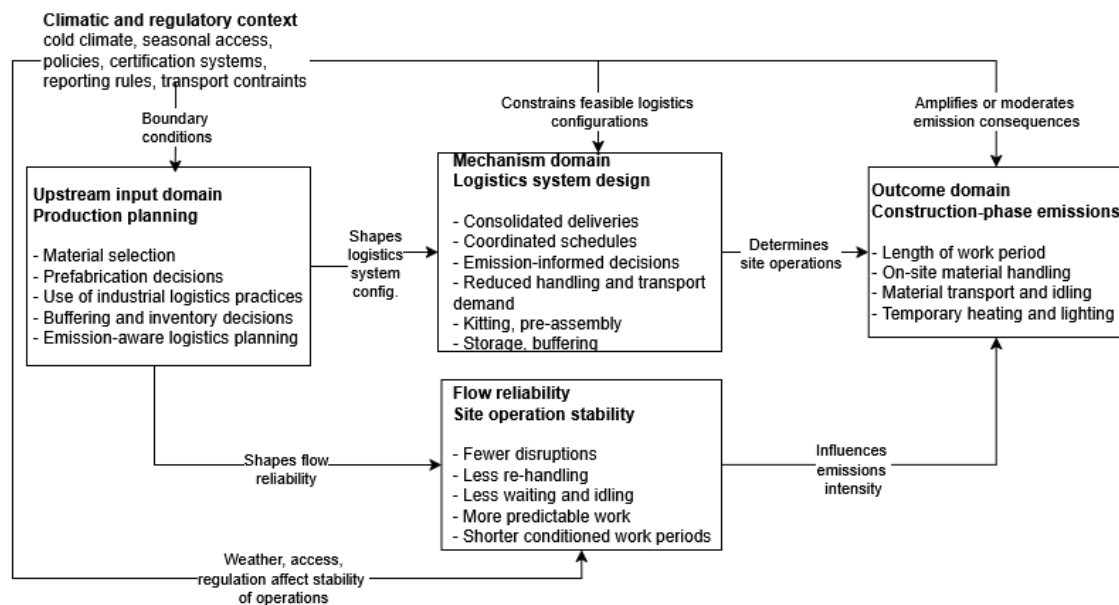


Figure 2: The framework linking lean, logistics efficiency and construction phase emissions

The framework shows how upstream design and production planning decisions influence construction phase emissions through two main pathways. First, they shape logistics system design, including delivery consolidation, kitting, storage and transport coordination, which affects transport volumes, handling intensity and site duration. Second, they influence flow reliability and site operation stability, which determine the extent of buffering, rehandling, waiting and temporary energy use. Climatic and regulatory conditions act as boundary factors that amplify or moderate these effects, particularly in cold climate contexts where delays prolong heating, lighting and enclosure needs. Overall, the framework highlights that reducing construction phase emissions depends not only on fuel or energy choices, but on how materials, production and logistics are configured upstream.

DISCUSSION

IMPLICATIONS FOR LEAN THEORY

This study contributes to lean construction research by making explicit the link between lean practices and construction phase emissions. More specifically, it identifies logistics system design as the missing mechanism connecting upstream design and production planning decisions with downstream A4–A5 emission outcomes. The findings also highlight climate amplification effects: in cold climates, disruptions in flow and poor logistics integration have stronger emissions consequences as delays extend temporary energy use and site operations.

Lean production models such as the Portfolio–Process–Operations (PPO) framework offer complementary perspectives. It emphasizes the interaction between multi-project portfolios, process flow and operational stability in construction systems that provides a strong foundation

for understanding logistics coordination and flow (Korb et al., 2017). The present study extends this by explicitly incorporating construction phase emissions and cold climate conditions.

Lean construction research has long emphasized the role of logistics and material flow in improving production efficiency and workflow reliability. This study builds on that foundation by showing that flow reliability is also emissions-relevant, and that production planning decisions shape emissions through their effects on logistics system design, site stability and temporary energy demand.

IMPLICATIONS FOR PRACTICE AND POLICY

The cross-country insights illustrate different practical and policy conditions under which logistics inefficiencies are governed, measured and mitigated. Finland demonstrates relatively strong institutional coordination, where logistics planning and circular material flow strategies can function as decarbonization mechanisms. Estonia shows comparatively strong digital maturity in freight and logistics monitoring, improving the visibility of transport activity, although explicit integration with construction phase emissions assessment remains limited. Canada highlights a different challenge: in remote northern regions, seasonal access constraints create a structural mismatch between logistics access and construction timing, increasing the need for early delivery, storage and buffering, thereby contributing to higher A4–A5 emissions.

For practice and policy, the findings suggest that logistics should be treated as a design parameter rather than only as a site-level operational issue. This implies integrating logistics planning earlier into design, procurement and production planning; incorporating lean flow design into emissions mitigation strategies; and developing certification and LCA approaches that recognize logistics process improvements as legitimate emission-reduction measures.

Logistics decisions must therefore be embedded upstream, not only managed reactively on site (Andersson & Nilsson, 2018). Early integration of logistics expertise can support design for kitting and preassembly, coordination with transport and crane capacity, layout design compatible with takt zones, and material flow standardization that enables JIT delivery. Such measures reduce unnecessary handling, redundant transport, temporary works and energy-intensive site duration, offering a practical complement to lean site-level practices.

CONCLUSION

This study proposes a framework explaining how construction phase emissions are shaped by upstream design and production planning decisions, logistics system design, and climatic and regulatory conditions. The framework shows that emissions reductions are not merely a by-product of efficient logistics, but depend on how materials, production and logistics are configured early in the project. In cold climate contexts, where seasonal access constraints and temporary energy demands amplify the effects of logistics inefficiencies, emission-aware planning becomes particularly important. By identifying logistics system design as the mechanism linking upstream planning choices with A4–A5 emissions, the study contributes to the literature by shifting attention from measuring construction phase emissions to explaining how they are generated. Practically, the findings indicate that meaningful emissions reductions can be achieved by embedding logistics considerations into early design and planning. This study is limited by its conceptual and integrative design, which does not quantify the relative effects of specific design, planning or logistics interventions. Future research should test and refine the framework through empirical studies and quantitative assessment of how such decisions influence emissions across different project and climatic contexts.

ACKNOWLEDGEMENTS

This work has been supported by the Estonian Research Council grant (PSG963).

Müge Tetik acknowledges financial support from Foundation for Economic Education (Liikesivistysrahasto) for conference participation

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