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RESEARCH ARTICLE

Logistics for Building Circular, Biobased, and Modular: Environmental Impacts in Amsterdam

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Abstract

Circular, biobased, and modular construction practices are gaining traction as cities seek to reduce the environmental impact of the built environment. However, little is known about how these strategies affect construction logistics and their associated emissions. We develop an agent-based model to assess the environmental and spatial impacts of construction logistics in the Amsterdam Metropolitan Region (AMA) under six future scenarios. These scenarios vary in transport modes, construction practices, and logistics hub configurations. Results show that modular construction significantly reduces emissions through delivery consolidation, while circular and biobased approaches present trade-offs. Circular logistics reduce total emissions by sourcing materials locally but increase local emissions and congestion due to more frequent, short-distance trips in case of fossil transport. Biobased construction reduces transport emissions because of lower weight but may increase emissions when materials are sourced from distant suppliers, often located abroad, e.g. in Austria. The study also reveals that water transport lowers CO_2 but often raises NO_x and PM emissions in case of use of ships with older engines. Also, decentralized logistics networks may perform worse than centralized ones without advanced coordination. These findings emphasize that sustainability benefits depend not just on what is built, but how and where materials are transported. Policymakers and urban planners must weigh both global and local trade-offs when designing logistics systems for sustainable construction. Our model offers a data-driven framework to support such decisions, highlighting the need for integrated, spatially grounded planning approaches in the circular transition.

Keywords Circular Built Environment · Construction Logistics · Agent-based Modeling · Urban Sustainability · Modular Construction · Biobased Materials · Transport Emissions · Reverse Logistics · Circular Economy · Circular Hubs.

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Introduction

The built environment contributes substantially to global emissions and resource consumption (Cabeza et al., 2014; Pomponi & Moncaster, 2017; United Nations Environment Programme & Yale Center for Ecosystems + Architecture, 2023). Creating a circular built environment (CBE) has become a key priority for cities and countries, prompting policies aimed at fostering circularity in construction and demolition (European Commission, 2020; Waterstaat, 2019; European Commission, 2023; World Green Building Council, 2023). In academic literature, CBE strategies can be categorized into three main types: slowing, narrowing, and closing material loops. Slowing loops refers to extending the lifespan of materials and buildings through maintenance, repair, and reuse. Narrowing loops involves using fewer resources through efficient design and construction processes. Closing loops focuses on recycling and recovering materials to reintroduce them into the production cycle, thereby minimizing waste and reducing the need for virgin inputs (Geissdoerfer et al., 2017; Pomponi & Moncaster, 2017).

In this paper, we focus on one specific aspect of circularity: closing material loops by reusing demolition waste in new construction. Closing material loops introduces new opportunities and challenges for logistics systems, particularly in dense urban areas where spatial and infrastructural constraints complicate the movement of materials (Ghisellini et al., 2016; Ripanti & Tjahjono, 2019; Seroka-Stolka & Ociepa-Kubicka, 2019; Van Buren et al., 2016; The International Transport Forum, 2024; Andruetto et al., 2024). Effective reuse of demolition waste requires coordinated logistics systems capable of collecting, sorting, storing, and redistributing materials to construction sites in a timely and efficient manner.

One proposed solution is the use of circular construction hubs, which act as intermediaries between demolition and construction activities. These hubs enable material consolidation, quality assessment, and temporary storage, facilitating the integration of secondary materials into new projects (Tsui et al., 2023; Uden et al., 2025). Despite growing interest in circular hubs, research has primarily focused on their economic and operational feasibility, with limited attention paid to the urban and environmental impacts of their logistics. As the urgency of climate mitigation grows, understanding the emissions trade-offs associated with different logistics configurations becomes increasingly important.

At the same time, the built environment is becoming increasingly digitized. Emerging data sources—such as construction material passports, digital twins, and open-access urban data—present new opportunities for evaluating and optimizing logistics systems in circular construction. Digital technologies can support decision-making by providing granular insights into material flows, transportation needs, and emissions consequences across different scenarios (Çetin et al., 2021; Harmelink et al., 2025).

In this study, we explore how circular, biobased, and modular construction practices affect the environmental impact of logistics in the Amsterdam Metropolitan Region. We focus specifically on the role of circular hubs in reducing transportation-related emissions and evaluate the effectiveness of various construction methods and transport modes using an agent-based modeling approach. In doing so, we aim to advance the understanding of circular construction logistics and contribute to the development of data-driven strategies for sustainable urban development.

Theoretical Background

While reuse in construction has long existed, circular construction logistics has only recently gained focused attention. Historically, logistics emphasized forward flows—delivering new materials—while reverse flows (retrieving reusable materials) were secondary (Ding et al., 2023). This began to shift in the 2000s with design for deconstruction and take-back schemes, laying the groundwork for reverse logistics in construction (Ding et al., 2023). Policies like Japan's 3Rs (reduce, reuse, recycle) (Japan Ministry of Ecology, Trade, and Industry, 2024) and the EU Waste Framework Directive (European Commission, 2008) formalized waste reduction hierarchies, later expanding to the "10 R" frameworks prioritizing value retention from refuse to recover (Kirchherr et al., 2017). Recent research highlights Circular Logistics Integration (CLI) as key to coordinating demolition outputs with new construction inputs (Ding et al., 2023). Innovations such as cradle-to-cradle building design, deconstruction services, and reuse marketplaces have since emerged (Mrad & Frölén Ribeiro, 2022). Overall, logistics has evolved from a linear model to a dynamic, bidirectional system at the heart of circular construction, supported by both policy and technology.

Digital Tools for Circular Construction Logistics

Digital technologies are increasingly central to enabling circular logistics in construction. Rather than operating in isolation, these tools form a complementary system. Geographic information systems (GIS) and building information modelling (BIM) provide the digital infrastructure by storing and integrating spatial data at both the urban and building scale. Transport and material tracking systems build on this foundation by monitoring how materials actually move through the city today. Predictive systems then extend this view into the future, using data from GIS, BIM, and tracking to anticipate tomorrow's material flows and inform proactive logistics planning (Lee & Lee, 2021; Nag et al., 2025).

Digitized information systems provide essential data to optimize circular logistics. Geographic Information Systems (GIS), which are digital platforms for spatial analysis, support logistics by identifying reusable material resources, enabling efficient routing and proximity-based reuse. GIS also aids in selecting optimal locations for recycling plants, minimizing transport distances and environmental impacts (Tsui, Wuyts, et al., 2024).

Building Information Modeling (BIM), which provides digital representations of buildings containing detailed data, acts as a living inventory to streamline future deconstruction and material recovery. Integrated with planning tools, BIM facilitates designing buildings for disassembly, enhancing circular logistics by providing transparency and foresight into material flows (Honic et al., 2023).

Transport and Material Tracking Systems digitally trace materials throughout their lifecycle, improving circular construction logistics. Material passports store detailed information—type, quantity, location, recycling instructions—enabling quick identification and reuse of components (Hoosain et al., 2021; Walden et al., 2021). Blockchain provides transparent, immutable records of material provenance, ensuring trust in reclaimed materials and streamlining marketplace transactions via smart contracts (Kouhizadeh et al., 2020; Upadhyay et al., 2021). Internet of Things (IoT) tracks components in real-time through sensors and RFID tags, enabling precise inventory management, predictive maintenance, and efficient logistics coordination (Jum'a et al., 2024; Rejeb et al., 2022; Voulgaridis et al., 2022). Additionally, digital platforms facilitate efficient matching of supply and demand for reclaimed construction materials, further promoting circularity (Blackburn et al., 2023; Kovacic et al., 2020; Soldatos et al., 2021).

Predictive and analytics systems forecast and optimize circular logistics. Digital twins—dynamic virtual replicas of physical buildings—integrate sensor data to predict component lifespan and facilitate scenario-based decision-making (e.g., optimal refurbishment or component recovery) (Z. Chen & Huang, 2020; Meng et al., 2023; Preut et al., 2021). They enable adaptive management of circular processes through real-time "what-if" analyses. Agent-based modeling (ABM) simulates interactions between stakeholders, materials, and infrastructure, capturing complexities like timing mismatches and market dynamics (P. Chen et al., 2020; Clausen et al., 2019; Lange et al., 2021). ABM serves as a virtual laboratory to test circular strategies, identify bottlenecks, and explore the impact of policies and business models on construction logistics.

Methods Supporting Circular Construction Logistics

Beyond digital tools, several methods and frameworks have been developed to support circular logistics in construction. Urban mining approaches provide the data foundation by mapping material stocks and flows, making it possible to identify what materials need to be moved, in what quantities, and from where. Building on this information, optimization of material flows focuses on how logistics systems can be designed to transport these resources efficiently across urban space. One key strategy within this optimization is the development of circular hubs—storage and logistics facilities located in or near city centers that consolidate materials, reduce redundant transport, and facilitate reuse within the built environment.

Urban mining treats cities as future sources of raw materials by viewing buildings as repositories of reusable materials. Dynamic Material Flow Analysis (dMFA) supports this by forecasting the type, quantity, and timing of materials released through renovation or demolition. Studies have been conducted in a number of countries, including China (Hu et al., 2010; Huang et al., 2013), Japan (Hashimoto et al., 2007), Germany (Schiller et al., 2017), and Norway (Bergsdal et al., 2007). These predictive models are crucial for circular construction logistics: they help identify demolition hotspots, plan collection infrastructure, and anticipate secondary material supply. Recent work also considers material quality, supporting reuse over recycling where possible. Overall, dMFA enables a proactive, strategic approach to circular logistics—aligning material recovery with future construction demand and informing policies for sustainable urban development.

As circular practices scale up, efficient logistics are essential to reduce the environmental and financial costs of transporting secondary materials (Ding et al., 2023). Optimization models help design circular supply chains that balance emissions, distance, time, and cost. An example is the Timber Loops project (Tsui, Venverloo, et al., 2024), which used spatial optimization to plan the flow of reclaimed timber in Amsterdam. By identifying optimal locations for storage and processing hubs, the study minimized transport distances and carbon emissions. Projects like these treat reverse logistics—matching used materials with reuse sites—as a supply-chain problem with constraints like storage limits and material decay. By aligning material flows with reuse opportunities, optimization supports low-impact circular logistics. More broadly, logistics studies also integrate multiple goals (e.g. emissions, cost, job creation), helping stakeholders make more holistic, sustainability-driven decisions (Bartolacci et al., 2012; W. Chen et al., 2024; Malladi & Sowlati, 2018).

Circular construction hubs serve as centralized locations for collecting, processing, and redistributing reclaimed building materials, streamlining logistics and supporting circular supply chains. Rather than moving materials ad hoc between projects, hubs act as marketplaces and storage centers. Tsui et al. (2023) identify four types: urban mining hubs (near demolition sites), industry hubs (for large-scale material upscaling), craft centers (for refurbishing components), and local material banks (temporary storage). These hubs reduce transport needs, improve material quality control, and support reuse-oriented business models. However, challenges remain: hubs require a steady material flow to be viable, and coordination among stakeholders is often lacking. Urban space constraints, inconsistent reuse demand, and limited market trust also pose barriers. Still, early pilots in Europe show promise. Recent studies apply data-driven modeling to support strategic hub siting based on spatial, logistical, and market dynamics (Tsui, Venverloo, et al., 2024; Yang et al., 2023; Yu et al., 2024). Hubs bridge theory and practice in circular construction logistics—enabling efficient reuse, fostering new markets, and supporting long-term shifts toward designing for reuse. Hybrid models and supportive policies are key to scaling their impact.

Case study Amsterdam Metropolitan Region

Housing shortages in major European cities have worsened in recent years. In the Netherlands, over 300,000 new homes—more than 4% of the current stock—are needed, especially in the densely populated Randstad, including Amsterdam, Rotterdam, The Hague, and Utrecht. To meet this demand, these cities aim to build 30,000 homes annually by 2030 (Groenemeijer et al., 2021). In Amsterdam, this creates a dual challenge: expanding housing supply while reducing construction-related environmental impacts. Strategies to address both goals include high-rise development, and the adoption of circular, biobased, and modular construction, and low-emission logistics.

High-rise buildings face specific challenges in meeting Paris Proof targets and complying with carbon calculation methods (Dutch Green Building Council, 2025). This has driven interest in low-carbon materials such as mass timber. Engineered wood products like cross-laminated timber (CLT) and glued laminated timber (glulam) have lower carbon footprints and are lighter than concrete (Dias et al., 2016), making them suitable for sustainable high-rise construction (Ilgın, 2023).

Amsterdam supports this shift through a Green Deal promoting bio based construction, with a goal for 20% of new housing to use timber by 2025 (Amsterdam Economic Board, 2022). Additionally, Amsterdam developed its Circular Economy strategy, aiming to become fully circular by 2050 (City of Amsterdam, 2020).

Further, modular construction brings several benefits such as faster construction, safer manufacturing, better quality control and lower environmental impact (Thai et al., 2020). Building modules can be disassembled and reused elsewhere, supporting CE aims. The Dutch government is promoting modular approaches as part of its broader circularity agenda (De circulaire bouweconomie, 2022).

To further reduce emissions, Amsterdam is introducing zero-emission zones for freight (City of Amsterdam, 2023) and developing logistics hubs, including those dedicated to construction (City of Amsterdam, 2021). These hubs support efficient deliveries via inland waterways, which already carry about 30% of construction materials and equipment in the Netherlands (Van Rijn et al., 2020).

High-rise construction (defined in Dutch policy as buildings taller than 30 meters) plays a key role in densifying the urban fabric. In this study, we use the future construction of high-rises in Amsterdam as a case study to explore how emerging construction practices—namely circular, modular, and biobased building approaches—affect the environmental footprint of construction logistics.

Research Gaps, Aim

Despite growing interest in circular construction logistics, two key research gaps remain. First, the spatial consequences of circular logistics are underexplored. While some studies have begun modeling hub locations, there is limited understanding of how circular logistics infrastructure could reshape urban space—such as its impact on road usage, traffic patterns, and related health outcomes, or how much land is needed to support logistics hubs, storage, and material flows across a city (Aljohani & Thompson, 2016; Tsui et al., 2024). Second, there is a lack of comprehensive environmental assessments of circular logistics systems (Aung et al., 2025). Most studies focus on narrow aspects—such as a single product type, transport mode, or business model—yet cities need a holistic view to compare different options (Andruetto et al., 2024). Choices about transport (e.g. road vs. water), construction material type (biobased vs. mineral), fleet electrification, and hub design all influence environmental outcomes. A more integrated approach is needed to support strategic planning for sustainable urban logistics systems.

In this study, we therefore aim to:

- Quantify the environmental impacts of construction logistics for high-rises in Amsterdam under different scenarios, considering variations in construction materials (circular, biobased, modular), transport mode, material type, hub usage, and system design.
- Assess the urban consequences of implementing circular logistics in the city, including impacts on road usage, pollution, and infrastructure requirements.

Methodology

The methodology described below outlines the approach we used to estimate emissions related to construction logistics in the Amsterdam Metropolitan Region (AMA) for the period 2023-2035. We designed an agent-based model to simulate logistics movements under various future scenarios. The Python script and data used for this agent-based model can be found on github.com/TanyaTsui/bimzec.

Parameter and Scenario Setting

The model parameters were determined through a series of meetings with key stakeholders in the Amsterdam region. Participants included municipal staff involved in planning new circular hubs, academic experts in logistics, and companies operating within construction logistics. The parameters were designed to reflect realistic logistical and construction scenarios relevant to the region.

Two main types of parameters were defined:

- Logistics Parameters: These include the hub network (no hub, centralized hub, decentralized hub), the transportation network (road, water, rail), and truck type (diesel, semi-electric, full electric).
- Construction Parameters: These involve the extent of biobased material use (none, full), modularity (none, full), and circularity (none, semi, full, extreme).

For more details on each parameter, refer to our supplementary document, Table 1.

Given the wide range of possible parameter combinations, it was not feasible to model every scenario. Instead, we co-developed six representative scenarios with stakeholders. The number was intentionally restricted to balance analytical depth with stakeholder relevance and communicability.

The chosen set reflects the most policy-relevant levers identified in practice—introduction of hubs, electrification of vehicles, waterborne transport, modular and circular construction—and their combinations. While additional scenarios could in principle have been explored, these six already span the main strategic options under consideration and provide a representative picture of potential system trajectories. The parameters defining each of the six scenarios are summarized below in Table 1.

Table 1 Overview of scenario parameters used in the agent-based model, ranging from business-as-usual (S1) to highly circular, modular, and biobased construction (S6). Each scenario varies across six key dimensions: hub network, transport network, truck type, biobased material type, modularity, and degree of circularity.

	Hub network	Network type	Truck type	Biobased type	Modularity type	Circularity type
S1	none	road	diesel	conventional	conventional	conventional
S2	centralized	road + water	diesel	conventional	conventional	conventional
S3	centralized	road + water	semi	conventional	conventional	conventional
S4	centralized	road + water	semi	biobased	conventional	conventional
S5	centralized	road + water	electric	biobased	modular	conventional
S6	centralized	road + water	electric	biobased	modular	extreme

Model Workflow

The model estimates the environmental impact of each scenario using a four-step simulation process:

- Set Parameters: For each scenario, the relevant logistics and construction parameters are defined.
- Create Agents: The model generates agents representing construction hubs, construction sites, and material suppliers. An overview of the agents can be found below in Table 2.
- Simulate Agent Behavior: The model runs the simulation from 2023 to 2035. During this period, agents interact, triggering material transport between locations. Each movement is logged for emissions calculation.
- Calculate and Display Results: Outputs include total emissions over the simulation period, quantities and types of construction materials used, and spatial visualizations such as road usage maps and the locations of construction sites, suppliers, and hubs. Emissions are calculated at two scales: globally, and with the AMA.

After agents are created, the model simulates their behavior over a period of 12 years. The agent-based model simulates the behaviour of five key agent types: construction sites, macro hubs, macro assembly hubs, micro hubs, and suppliers. Construction sites request materials between their designated start and end years, based on parameters like biobased content. Macro hubs serve as intermediaries, collecting materials from suppliers or demolition sites and redistributing them to construction sites or micro hubs. They improve logistics by consolidating shipments and operate with 60–100% truck fill rates, depending on material type. However, bulk materials (e.g., cement, gravel) bypass hubs and are sent directly to sites. Macro assembly hubs appear only in modular construction scenarios. They receive flat-packed 2D modules, assemble them into 3D forms, and deliver them to construction sites. Due to space constraints, one truck can carry only two assembled modules. Micro hubs, used in decentralized logistics scenarios, aggregate requests from nearby construction sites and fetch materials from macro hubs. Suppliers provide specific material types (e.g., steel, timber) based on real-world locations. In scenarios without hubs, materials are delivered directly to sites with low truck efficiency (30% fill rate). In hub-based scenarios, bulk materials go straight to sites, modules to macro assembly hubs, and all other materials via macro or micro hubs, depending on the network configuration.

Table 2 Description of the six agent types in the agent-based model used to simulate circular construction logistics. Agents include logistics hubs (macro, macro assembly, and micro), construction sites, suppliers, and demolition sites.

Overview of agents	
Macro hub	Macro hubs are large logistics facilities for distributing construction materials. They collect materials from suppliers or demolition sites and send them to construction sites. There are two fixed macro hubs serving the AMA in this model.
Macro assembly hub	Macro assembly hubs are facilities that do pre-assembly work for modular construction. These hubs collect materials from suppliers, pre-assemble modules, and transport these modules to construction sites. There is one macro assembly hub in this model.
Micro hub	Micro hubs are smaller, district scale facilities that collect materials from macro hubs to send to construction sites. There are 140 potential locations for micro hubs in the AMA.
Construction site	Construction sites are where (biobased) high-rise buildings are being built. The construction period is typically 2-3 years, and construction start times vary. Each construction site is assigned to the closest micro, macro, and macro assembly hub.
Supplier	Material suppliers send materials to hubs or construction sites, depending on the model scenario. They are mostly located within the Netherlands, and are between 5 - 100 km from the AMA. The two exceptions are suppliers for biobased materials (Austria) and modular parts (Germany).
Demolition site	Demolition sites provide secondary material in circular scenarios. Hubs collect materials from demolition sites and send them to construction sites. Locations of future demolition sites are obtained from (Oorschot et al. 2023).

Every time materials are transported between suppliers, demolition sites, hubs, and construction sites, the model calculates associated transportation emissions. Four types of emissions are calculated: CO2 (carbon dioxide), NOX (nitrogen oxides), PM2.5 (particulate matter with diameters of ≤2.5 µm), and PM10 (particulate matter with diameters of ≤10 µm). Emissions are calculated according to the following formula:

$$E_t = \frac{M}{C \cdot P} \cdot D \cdot E_c$$

Where:

- Et = total emissions (tons or kgs of CO2, NOX, PM2.5, or PM10)
- M = amount of material transported (tons)
- C = truck capacity (tons). This is determined by which truck is being used to transport the materials, as each material is transported by a different type of truck. For more details see “vehicles info” row in table 2.
- P = average fill percentage (%). This depends on the type of material being transported, as not all materials can be efficiently fitted into a truck. For example, trucks transporting prefabricated concrete elements are usually only ~60% filled, because of the irregular shape of the elements. For more details, see the “materials logistics info” row in table 2.
- D = distance travelled (km). The model finds the distance travelled by calculating the fastest route between two agents on the road network, using the Dijkstra algorithm. This is done using road

network data downloaded from OpenStreetMap (OSM) with Python library "OSMnx". Only larger roads for heavy vehicles were included in the road network.

- Ec = emissions coefficient (tCO2 / NOX / PM2.5 / PM10 per km). This measures the amount of pollutants emitted for every kilometer traveled by a vehicle. This number depends on the type of material being transported, as each material is transported by a different type of vehicle.

Data Used

A variety of datasets were required to accurately simulate construction logistics and calculate environmental impacts. Collected data provided information on logistics, construction, demolition and materials.

For logistics data, we collected emissions factors per kilometer for different transport modes, including trucks, waterborne vessels, and trains. We also determined the material transport capacity of each vehicle type, accounting for both weight and volume constraints to reflect realistic logistics operations.

Construction data focused on the material composition of high rise buildings, including circular, modular, and biobased designs. We used profiles developed from actual buildings in Amsterdam, where we collected material information from interviews with local demolition contractors and construction experts.

Material and spatial data were equally important. Supplier locations were identified through interviews with industry stakeholders, while the locations of macro hubs were derived from current municipal plans. Micro hub locations were selected based on existing industrial sites across the AMA. Data on the number of future highrise constructions and construction site locations came from municipal planning documents. Finally, predicted demolition sites and material availability were informed by the study by Oorschot et al. 2024.

All data collected is available on our GitHub repository, in the "data" folder. The repository can be found at: github.com/TanyaTsui/bimzec.

Results

In this section, we present the environmental impact—measured in CO_2, NO_x, $PM_{2.5}$, and PM_{10}—of construction logistics across six scenarios (for details, see the Methodology section, Scenario Setting). The results are summarized for two spatial scales: (1) the full model, which includes logistics movements beyond the Amsterdam Metropolitan Region (AMA), and (2) the AMA itself.

Emissions for the Full Model

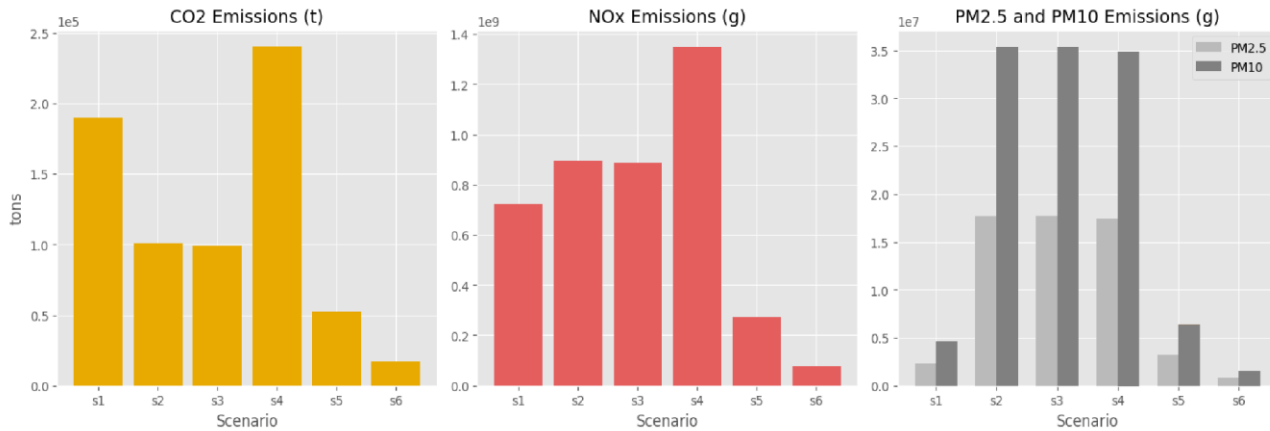

Fig. 1 Emissions associated with construction logistics across six modeled scenarios: CO_2 emissions (left), NO_x emissions (center), and $PM_{2.5}$ and PM_{10} emissions (right). CO_2 emissions are measured in tons, while other emissions in grams. Each bar represents total emissions from all transport movements within the model.

In the model, each scenario introduces parameter changes that affect emissions outcomes, as seen in Figure 1. Scenario 2 adds logistics hubs and uses the water network, reducing CO_2 emissions by decreasing transport movements but increasing NOx and PM emissions due to the higher pollutant output of ships compared to trucks. Scenario 3 introduces semi-electric trucks within the ring road around the city (A10 highway), but emissions remain largely unchanged since most transport occurs outside this zone. In Scenario 4, buildings are constructed with biobased materials, resulting in a significant emissions increase due to long transport distances from the timber supplier. Scenario 5 adds electric trucks for all movements within the AMA and modular construction, substantially reducing emissions due to the use of a single module supplier (for all components except the foundation), despite the supplier being located in Germany. Finally, Scenario 6 incorporates circularity, further lowering emissions by reducing travel distances between demolition sites and suppliers.

Emissions Within the AMA

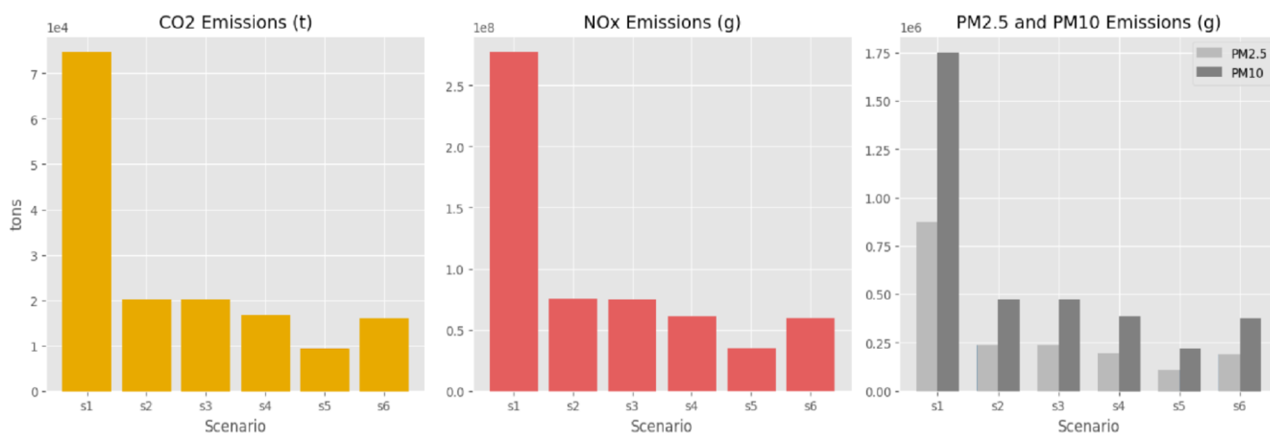

Fig. 2 Emissions from construction logistics within the Amsterdam Metropolitan Region (AMA) across six modeled scenarios: CO_2 emissions (left), NO_x emissions (center), and $PM_{2.5}$ and PM_{10} emissions (right). CO_2 emissions are measured in tons, while other emissions in grams.

The results for the AMA largely follow the same pattern as those for the full model, with a few key differences, see Figure 2. There is no significant increase in emissions between Scenarios 3 and 4. This is because the emissions increase associated with biobased materials stems mainly from the journey between the Austrian supplier and the logistics hubs—most of which occurs outside the AMA. Also, there is a slight increase in CO_2 emissions between Scenarios 5 and 6, when circular materials are introduced. Collecting materials from demolition sites leads to more transportation movements within the AMA. Since each demolition site provides only a limited amount of material, more trips are needed, although each trip is shorter. This reduces total emissions overall but results in a small increase within the AMA specifically.

Effect on Road Congestion

To understand how the addition of a hub affects traffic movements, we analyzed the model's road usage for a district in Amsterdam - Zuidoost. Here, three scenarios were simulated: (1) no hub; (2) one (non-circular) logistics hub that collects materials from suppliers and distributes them to construction sites; and (3) one circular hub that collects materials from both suppliers and demolition sites. For each scenario, the model recorded how often each road was used. Figure 3 below compares road usage across the three scenarios, using the scenario without a hub ("No hub") as the baseline.

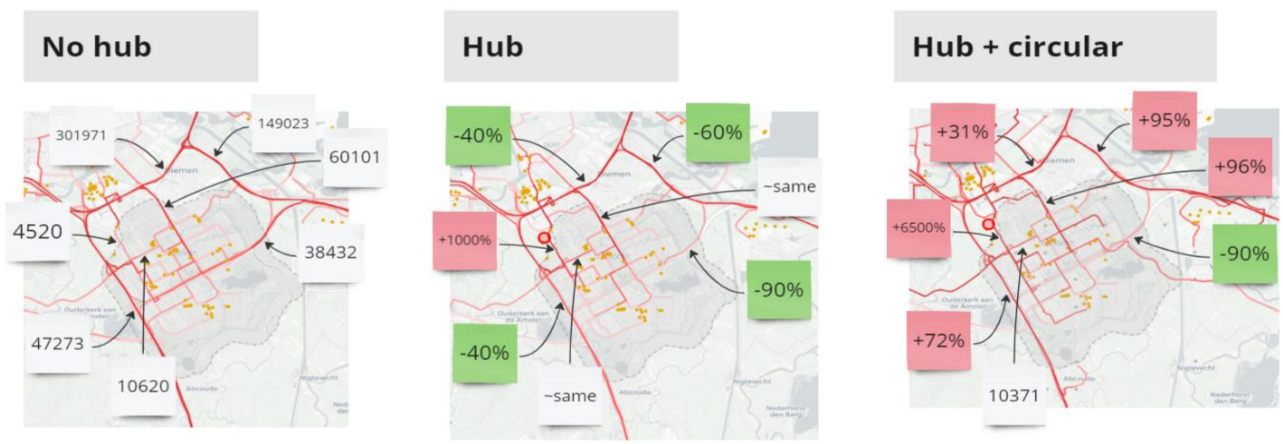

Fig. 3 Change in road usage, measured in number of truck movements, in Amsterdam Zuidoost under three logistics scenarios: (1) no logistics hub (baseline), (2) a central hub without circular material handling, and (3) a central hub with circular material handling. Values indicate relative change in road traffic intensity compared to the no-hub baseline.

As shown in Figure 3, adding a hub without circularity reduces road usage across most roads in Zuidoost, except those immediately adjacent to the hub on Holterbergweg. The decrease is especially significant along one of the main east-west corridors of the district, the Gaasperdammerweg, where usage drops by approximately 90%. However, when the hub also supplies circular materials, road usage increases on most roads. Usage of major highways such as the A2, A1, and S112 nearly doubles, and usage of Holterbergweg increases by a factor of about 60. The only remaining traffic benefit is the continued reduction in usage of the Gaasperdammerweg.

Discussion

Our results offer insights into how different construction practices and logistical strategies affect emissions. In this section, we discuss these insights, grouped into two main themes: (1) the impact of circular, biobased, and modular construction on logistics emissions, and (2) broader logistics choices and their environmental trade-offs.

Circular, Biobased, and Modular Buildings: More Complex than Expected

One of the central goals of this study was to understand how circular, biobased, and modular construction methods affect logistics emissions. While some results aligned with expectations, others were counterintuitive.

Circular construction reduces global emissions but increases local emissions. Scenarios sourcing circular materials lead to lower overall emissions for logistics, because materials are no longer sourced from suppliers that are sometimes far away, but from the local area, within the AMA. However, each demolition site has a limited amount of materials, leading to more trips overall, increasing local emissions and road usage. In short: circular logistics leads to more trips, but each trip is shorter, see Figure 4. This tension is likely to become more relevant as cities transition to circular economy principles: emissions may improve globally, but with negative local side effects, such as increased traffic congestion or decreased air quality.

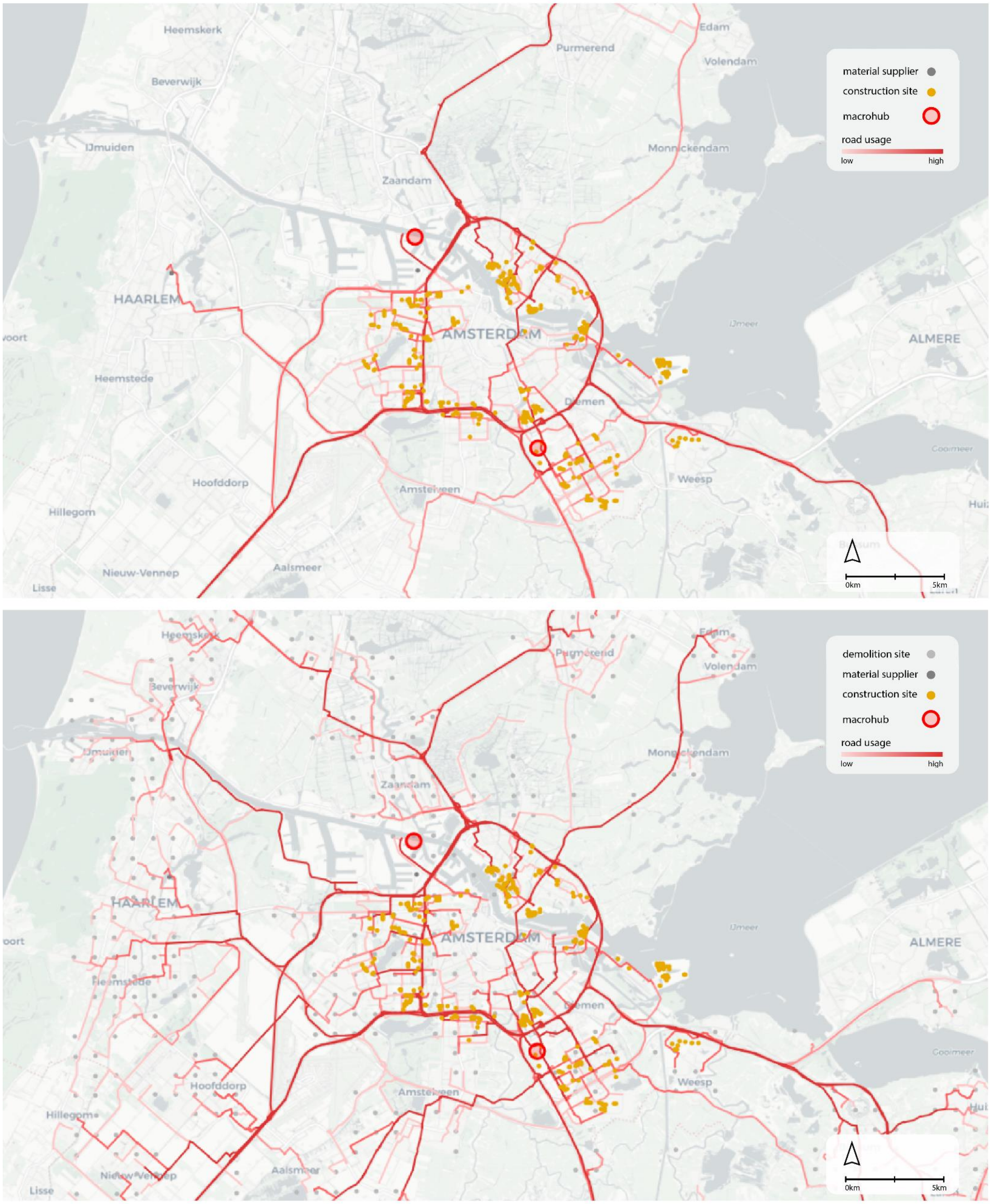

Fig. 4 Comparison of logistics-related transport movements within the Amsterdam Metropolitan Region (AMA) under two scenarios: logistics hubs without circular material reuse (left); and logistics with circular material sourcing from local demolition sites (right).

Higher levels of circularity did not lead to large emissions reductions. Although the model allowed for different levels of circularity—ranging from "none" to "extreme"—we found that switching to more ambitious circular scenarios did not significantly reduce emissions. Most emissions reductions occurred in the first step, from "none" to "semi" circularity, with only marginal gains beyond that. This unexpected plateau in emissions reduction is explained by the role of bulk materials (e.g., concrete, gravel, sand), which are not currently processed by circular hubs. Because these materials make up around 80% of a building's mass and are transported directly from suppliers even in "circular" scenarios, the overall impact of circularity remains limited. From a logistics perspective, expanding circular hubs to handle bulk materials could reduce emissions more substantially. However, this faces significant economic barriers: bulk materials are low in value and require a lot of space, making it difficult to justify processing them within the high land-cost environment of urban areas.

Biobased buildings surprisingly lead to higher emissions, unless materials are sourced locally. Switching to biobased construction materials significantly increased logistics emissions by around 250%. This was surprising, as timber is lighter than conventional materials and should reduce overall transport loads. However, the source of the timber played a much bigger role: the main supplier was in Austria, roughly ten times farther from the AMA than conventional suppliers. This finding highlights that emissions depend not just on what materials are used, but where they come from. Biobased construction may only offer logistics-related emissions benefits if the materials are sourced locally.

Modular construction significantly reduces logistics emissions. In contrast to the complex trade-offs found in circular and biobased construction, modular buildings consistently led to lower emissions. Switching to modular high-rises cut logistics emissions by half, even though the supplier was located in Germany. This efficiency comes from fewer, more consolidated deliveries: instead of transporting diverse materials from multiple suppliers, most of the building arrives as prefabricated modules, streamlining the entire process.

Trade-offs in Logistics Choices

Beyond construction methods, our study also investigated how different logistics strategies affect emissions. Again, we found important trade-offs between different types of pollutants, and between local and global benefits.

Water transport reduces CO_2, but increases NO_x and PM emissions. Using ships instead of trucks for material transport substantially reduced CO_2 emissions (by around 50%), but increased NO_x, $PM_{2.5}$, and PM_{10} emissions—by up to 775%. These results reinforce the global-versus-local tension seen earlier: water transport lowers greenhouse gases but introduces local air pollution that could harm public health.

Electrifying transport has limited impact due to long-distance diesel use. Switching to electric transport across the logistics chain only reduced emissions by around 2.5%. This is because the model assumes that long-distance trips remain diesel-fueled, even in electric scenarios. As a result, only intra-AMA transport is electrified, limiting overall impact.

A decentralized hub network increases emissions—contrary to expectations. We also found that using a decentralized network of macro and micro hubs led to higher emissions compared to a simpler, centralized hub system. This was surprising, since micro hubs are often promoted for improving last-mile efficiency. The likely reason lies in the model's current logic: hubs are assigned based on proximity, without optimizing for trip consolidation, see Figure 5. More sophisticated coordination strategies may still unlock the potential of decentralized hubs. Until then, these results suggest caution in assuming that decentralization will automatically lead to better outcomes.

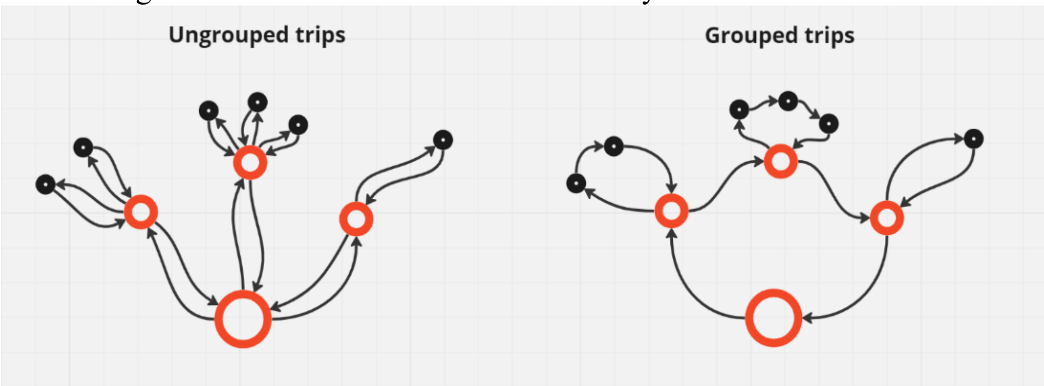

Fig. 5 Comparison of ungrouped versus grouped trips.

Broader Implications

Although our study is focused on Amsterdam, the results point to lessons for other European port cities and dense metropolitan regions aiming to cut construction emissions. Hubs can reduce the number of trips by consolidating deliveries, but the overall climate benefit depends on which transport modes are used. For example, shifting loads to older inland vessels lowers CO_2 but increases NO_x and PM, showing the need to combine hubs with cleaner vessels. Modular construction stands out as a robust option, since larger, consolidated deliveries consistently reduce emissions. Circular sourcing shortens supply chains and lowers total emissions, but also increases local trips and air pollution, meaning cities should plan for these side effects. Biobased construction only has clear benefits if supply chains are regional—long-distance transport quickly cancels out the gains. Finally, decentralised hubs and city-only electrification bring limited impact unless paired with coordination across regions and longer-distance clean transport.

The findings also speak to how circular economy policies are put into practice. Circular strategies that increase material flows back into cities need to be supported by clean last-mile rules, hub planning, and traffic measures to avoid congestion and pollution. Policies should combine measures that cut the number of trips (like modular construction) with measures that reduce emissions per trip (like electrification or clean vessels). Bulk materials remain a major blind spot, since they account for most of the construction mass but rarely pass through hubs; addressing this will be crucial for bigger logistics gains. Supporting regional suppliers can also help ensure that circular and biobased materials deliver real climate benefits rather than being offset by long-distance transport. Finally, making data and models openly available allows other cities to adapt this type of analysis and test their own policy options.

Limitations and Further Work

Our model has several limitations. Firstly, the quality of data used by the model is limited in several areas. The material composition of biobased buildings was estimated through meetings with a biobased building expert, rather than based on literature or average values from typical biobased buildings. Similarly, material logistics information—such as the typical fill percentage of different materials during transport, whether materials make use of hubs, or how materials move via water or rail—was estimated through expert consultation, as published data or surveys were not available.

Supplier locations were also simplified: for each material, we assumed it originated from a single, real-life supplier, although supplier locations vary per project and contractor. Another concern is the particulate matter (PM) emission coefficients for ships, which appear significantly higher than those for trucks. These values come from different sources and should be verified for consistency.

Secondly, the model does not fully account for the environmental and economic impact of hub infrastructure. While the model estimates transportation-related emissions, it excludes other potentially significant factors. The embodied emissions of construction materials—particularly the potential savings from using biobased or circular materials—were not included. These significantly influence the environmental profile of more circular scenarios. Similarly, emissions associated with construction machinery were not considered. Some building strategies, such as modular or biobased construction, may reduce machinery use, leading to lower emissions. Moreover, the model does not capture urban impacts such as noise pollution or road wear. Finally, additional financial costs required for hubs and electric vehicles were not included.

To further simplify the modeling process, several assumptions were made. Bulk materials, including concrete, sand, and gravel, were assumed not to be processed by hubs, since this is what currently happens in the market. This assumption significantly influenced the results, as bulk materials make up around 80% of a building's weight. Additionally, the allocation of transport movements was highly simplified: each construction site was assigned to its nearest micro hub, and each micro hub was linked to the nearest macro hub. This approach does not account for more efficient logistics strategies, such as multi-stop delivery routes or dynamic routing. The model also runs over a relatively long timescale (12 years), which enables projections into the future but limits the level of detail. Emissions are calculated annually rather than monthly or daily, meaning short-term changes in construction material demand or logistics intensity are not captured.

Finally, the model does not include a sensitivity analysis. The purpose of this study is to compare a set of stakeholder co-developed, policy-relevant scenarios rather than to test parameter robustness. Since the assumption that bulk materials bypass hubs reflects a structural constraint of current practice, and given current data uncertainties, varying this parameter would risk false precision rather than yield additional insight. A systematic sensitivity analysis remains valuable, but it lies beyond the scope of this study and is identified as a direction for future work.

Given these limitations, we suggest several directions for future research. First, the data used in the model should be improved and further verified by experts, especially concerning the composition of biobased buildings. Additional impact categories—such as embodied emissions or urban impacts—could also be integrated into the model if requested by policymakers. Future versions of the model could explore alternative hub network configurations to determine whether different setups lead to significantly different environmental or logistical outcomes. The functionality of hubs—such as whether they process bulk materials or offer electric vehicle charging—should also be reviewed in collaboration with experts. Sensitivity analysis of key assumptions should be included once data quality improves, to further test the robustness of outcomes. Finally, a more detailed model could be developed with a shorter time scale (e.g., monthly), to capture more granular variations in material flows and logistics patterns. The current model could also be tested with practitioners to evaluate its usefulness and identify opportunities for improvement.

Conclusion

This paper examined the environmental impacts of logistics in circular, biobased, and modular construction using an agent-based model developed for the Amsterdam Metropolitan Region. The model incorporated multiple stakeholder-informed parameters—such as transport mode, hub network, material type, and construction method—to simulate six future scenarios. Results showed that while sustainable construction strategies can reduce overall emissions, their logistical implementation introduces complex trade-offs.

Most notably, circular logistics reduced total emissions by sourcing materials locally but increased local road use and pollution due to more frequent trips from scattered demolition sites. Similarly, biobased construction unexpectedly led to higher logistics emissions, primarily due to long-distance timber transport from Austria. These findings highlight that environmental benefits depend not only on what materials are used but also where they come from and how they are transported. By contrast, modular construction consistently reduced logistics emissions by consolidating deliveries and shortening supply chains.

The study also revealed broader logistics trade-offs. Waterborne transport significantly reduced CO_2 but raised local NO_x and PM emissions. Decentralized logistics networks performed worse than centralized ones, suggesting that network design alone does not guarantee efficiency without smarter coordination. While the model has limitations—including simplified routing and emissions data—it provides a first-of-its-kind integrated view of construction logistics for circular transitions.

In conclusion, circular, biobased, and modular methods each offer sustainability potential—but only if their implementation is logistics-aware. Policymakers and planners must consider both global and local effects when designing future systems. Our study also suggests a shift in academic focus: from siloed analyses toward integrated, spatially grounded models co-developed with stakeholders. This holistic perspective is essential for guiding real-world decisions about where and how to build sustainable urban infrastructure.

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Data Availability All data and computational models supporting this study are publicly available in the GitHub repository (https://github.com/TanyaTsui/bimzec). Additional information regarding data collection and preprocessing can be obtained from the authors upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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