Supplementary Document

Scenario parameters

This supplementary document provides a technical description of the BIMZEC agent-based model. The purpose of this model was to estimate emissions associated with construction logistics in the Amsterdam Metropolitan Area (AMA) for the next decade. This was done by simulating logistics movements for different future scenarios. When using the model, users build their own scenarios by choosing options from a set of parameters, which are summarized in table 1 below.

Supplementary Table 1: Overview of parameters for model

Parameters overview		
Parameter	**Options**	**Description**
Hub network	None	There are no hubs in the AMA, so materials are sent directly from material suppliers to construction sites. This is how construction logistics works today.
	Centralized	There are two large “macro” hubs in the AMA, which collect some materials from suppliers and send them to construction sites. Hubs allow for higher efficiency in transportation – trucks are more likely to be loaded fully.
	Decentralized	There are two large “macro” hubs, as well as several “micro” hubs in the AMA. Micro hubs collect materials from macro hubs and deliver them to construction sites. They are located in industrial areas in the AMA.
Transportation network	Road	All transportation movements use the road network.
	Water	When possible, transportation movements use the water network. Materials are transported via water when: (1) suppliers for that material are known to use the water network, (2) when both the hub and the construction site are within 100m of the water network.
	Rail	When possible, transportation movements use the rail network. Materials are transported via rail when moving from suppliers to hubs, and only when suppliers of that material are known to use the rail network.
Truck type	Diesel	All transportation movements on the road use diesel vehicles.
	Semi	All road transportation movements within the A10 highway ring of Amsterdam use electric vehicles, while all other movements use diesel vehicles.
	Electric	All transportation movements between hubs and construction sites or demolition sites use electric vehicles. All movements between suppliers and hubs stay fueled by diesel.

Biobased type	None	Buildings use conventional materials and have a concrete structure and foundation.
	Full	Buildings use, where possible, biobased materials. This includes a timber structure and biobased building components.
Modularity	None	Buildings do not have modules and are built using conventional methods.
	Full	Buildings consist of a concrete core and modules that are pre-assembled at a construction hub, transported to site, and mounted on the structure.
Circularity	None	Buildings use conventional materials, meaning all materials come from material suppliers.
	Semi	All non-structural materials are sourced from demolition sites, except for materials that are not usually processed by hubs.
	Full	All non-structural and structural materials are sourced from demolition sites, except for materials that are not usually processed by hubs.
	Extreme	All non-structural, structural, and foundation materials are sourced from demolition sites, except for materials that are not usually processed by hubs.

Data

The Python script and data used for this model can be found on github.com/TanyaTsui/bimzec. An overview of data used can be found in Table 2 below.

Supplementary Table 2: Overview of data with source and description

Overview of data		
Name	**Source**	**Description**
Vehicles info	Institute for Road Safety Research (SWOV), Rijksoverheid, Emissieregistratie	Data on vehicle types, weight, total weight, total freight volume (m^3), and emissions per kilometer (CO_2, NO_x, PM). The dataset was compiled in collaboration with the Amsterdam University of Applied Sciences (HvA) using various Dutch government sources on transport and emissions.
Materials logistics info	Experts survey, internet research	Conducted with the expertise of HvA (Walther Ploos van Amstel and Michael Berden). Particularly for load factor assumptions. For max. load calculations, either m^3 or kg were applied, using standard kg-per-m^3 conversion factors for each material.
Building types – material composition	Environmental impact cost reports (from VolkerWessels, JP van Eesteren, LEVS)	Environmental impact cost reports from contractors and architects for several buildings were collected and translated into generic building types: mid-rise and high-rise, with distinctions between conventional, biobased, and modular construction.
Module info	Interview with Derix	Module information was gathered from the company (Derix) that designed the modules for Hotel Jakarta in

		Amsterdam; these dimensions and weights were used as the generic module.
Building types	Project data for Stepstone (LEVS), World of Food (LEVS), The Ensemble (Wonam). Data provided by external parties.	The team conducted data collection and analysis for various projects and defined three types (B, C, D — small, medium, large) to estimate future material needs and therefore transport movements for housing construction. For each type, a biobased variant was developed with the expertise of Stijn Brancart (TU Delft).
Suppliers	Netherlands Association of Supplying Building Materials Industry (NVTB)	Using trade association member lists for each material, suppliers closest to Amsterdam were identified and selected for the modelling. For mass timber, a major CLT producer in Austria was chosen as a common source, and for timber modules, the manufacturer's location in Germany was used.
Macro hubs	Large construction hubs: Amsterdam Logistic CityHub (operational) and DuraVermeer Hub Zuidoost (planned).	Locations were based on the existing macro hub in the Amsterdam port area (Amsterdam Logistic CityHub hub with VolkerWessels) and a planned future hub in Zuidoost with DuraVermeer and the City of Amsterdam.
Micro hubs	Scientific publication (Tanya Tsui et al., 2023)	Tanya Tsui et al. (2023) estimated potential micro-hub locations in the AMA region, which were used in this study (npj Urban Sustainability, *Spatial optimization of circular timber hubs*).
Construction sites	Municipality of Amsterdam; available as open data at data.amsterdam.nl	Data has information on locations, expected dimensioning (low-, mid- or high-rise), structural and non-structural type (conventional, modular, and/or biobased), and planned construction dates for all projects in the Amsterdam region over a 10-year period.
Demolition sites	Netherlands Environmental Assessment Agency (PBL)	This dataset (.shp) contains the location and quantities of materials available from the material stock in the AMA. For details on data generation, see the journal paper *Toward a low-carbon and circular building sector: Building strategies and urbanization pathways for the Netherlands* (van Oorschot et al. (2022), *Journal of Industrial Ecology*).

Agent definitions

The agent-based model consists of six agent types. Table S3 summarizes the role and characteristics of each agent.

Supplementary Table 3: Overview of agents in agent-based model

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 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.
Demolition site	Demolition sites provide secondary material in circular scenarios. Hubs collect materials from demolition sites and send them to construction sites.

Model workflow and agent behavior

This model uses agent-based modelling to simulate the behavior of construction sites, hubs, and suppliers, in order to estimate transportation emissions associated with construction. The Python library Mesa (https://mesa.readthedocs.io/) was used to construct the model. Agent-based modeling is a computational simulation approach used in various fields, where individual agents, such as people, animals, or entities, are represented with unique behaviors and interact with each other and their environment. This modeling technique enables the study of complex systems and emergent phenomena by examining the collective behavior that arises from the interactions of these autonomous agents.

In short, running the model consists of four steps. These four steps are further elaborated in the sub-sections below.

Step 1: Define parameters

In step 1, the user defines scenario parameters for the model. See table 1 (parameters overview) for a detailed description.

Step 2: Create agents

In step 2, the model creates the agents whose behavior will be simulated. An overview of the agents can be found below in Table 3.

Step 3: Simulate agent behavior over 12 years and record emissions

Once the agents have been created, the model simulates their behavior over a period of 12 years. Agent interactions govern material requests, transport, and hub operations during the simulation period. Table 4 below provides an overview of the behavior of agents in the model.

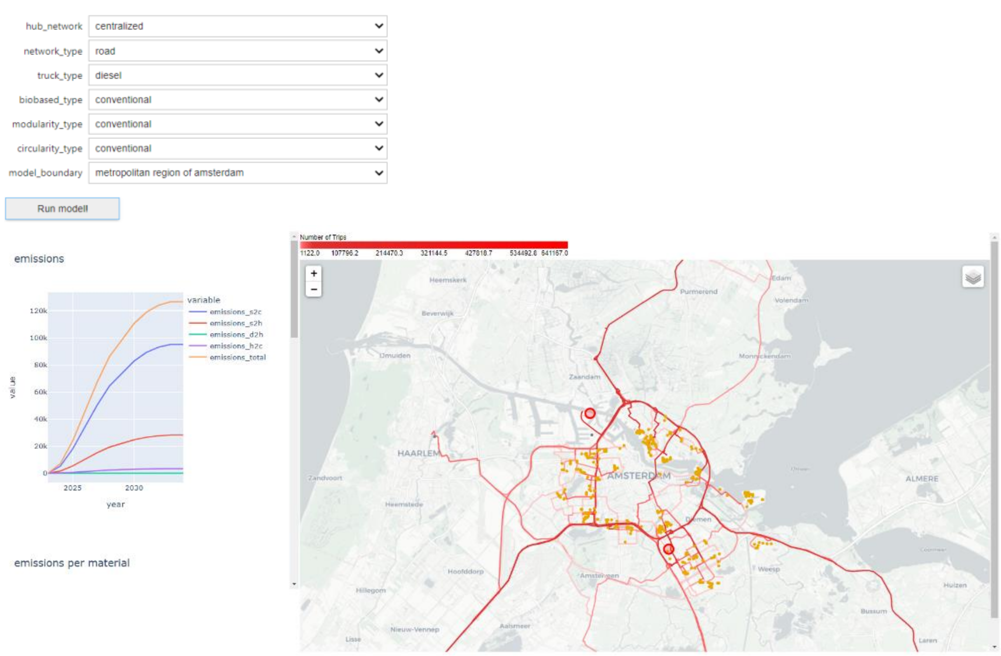
Supplementary Table 4: Overview of agent behavior during model simulation

Overview of agent behavior during model simulation	
Construction site	• Each construction site has an estimated start and end year for construction. When the simulation reaches the start year of the construction site, it will start to request materials for construction. • The materials requested depend on the "biobased" parameter set by the user, which determines whether the buildings will be biobased or not. • Once the simulation reaches the end year of the construction site, it stops requesting materials.
Macro hub	• Macro hubs look at nearby construction sites or micro hubs to see what materials are being requested. • Macro hubs then collect the requested materials from suppliers or demolition sites, depending on whether the user-chosen scenario includes circular construction • Macro hubs then send the collected materials to construction sites or nearby micro hubs, depending on whether the use-chosen scenario includes micro hubs (decentralized hub network). • Hubs provide more efficient logistics, as they can combine materials requests from many construction sites. The model therefore assumes that trucks transporting materials to and from hubs are 60-100% filled. The fill percentage varies according to material (see section "data", vehicles info). • Bulk construction materials (cement, concrete, gravel, and sand) are not processed by hubs. They are transported directly from suppliers to construction sites, regardless of whether the scenario includes hubs. See row "supplier" in this table.
Macro assembly hub	• Macro assembly hubs function similarly to macro hubs; expect they are only responsible for transporting building modules. They therefore only appear in the simulation when the user-chosen scenario includes modular buildings. • Modules transported from the module supplier to the macro assembly hub are in "2D" form, meaning the modules are not yet assembled and are loaded into trucks as flat components. • Modules are then assembled into "3D" modules and transported to construction sites. Since 3D modules take up more space, their transportation is less efficient. The model assumes that one truck can transport one module at a time.
Micro hub	• Micro hubs appear in the simulation when the user-chosen scenario asks for a de-centralized hub network.

	● Micro hubs look at nearby construction sites to see what materials are being requested. ● Micro hubs combine the materials requests from nearby construction sites and collect these materials from the nearest macro hub ● The collected materials are then sent to the construction sites that requested them.
Supplier	● Each supplier is responsible to supplying one type of material, e.g. steel, concrete, timber … etc. The supplier's location is based on locations of real suppliers. ● If the scenario does not include hubs, materials are sent directly from the supplier to construction sites. Because there is no coordination of logistics between different sites, the model assumes that transportation is relatively inefficient, and that trucks are only 30% loaded for each trip. ● If the scenario includes hubs, bulk materials are sent directly to the construction site, modules are sent to macro assembly hubs, and all other materials are sent to hubs.

Step 4: Display results

The model displays the results of the simulation. This includes the total emissions over the 12 years of the simulation, construction materials used, as well as a map showing roads used and locations of construction sites, hubs, and suppliers. We are currently working on an interactive webapp that allows users to select parameters and view results. The first version of the app can be found here. However, please note that the webapp is currently quite unstable – sometimes it can take a long time to load, or even not load at all. A screenshot of the webapp can be seen below, and a demo of the webapp can be found here.



Supplementary Figure 2: Webapp BIMZEC with parameters and results as data visualizations

Results

Six modeled scenarios

To illustrate the transition to a linear to a biobased and circular economy, we simulated 6 scenarios, with each scenario getting closer to circular and biobased construction. Table 5 below shows that parameters were chosen for each of the six scenarios.

Supplementary Table 5: Parameters chosen for 6 modeled scenarios

	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

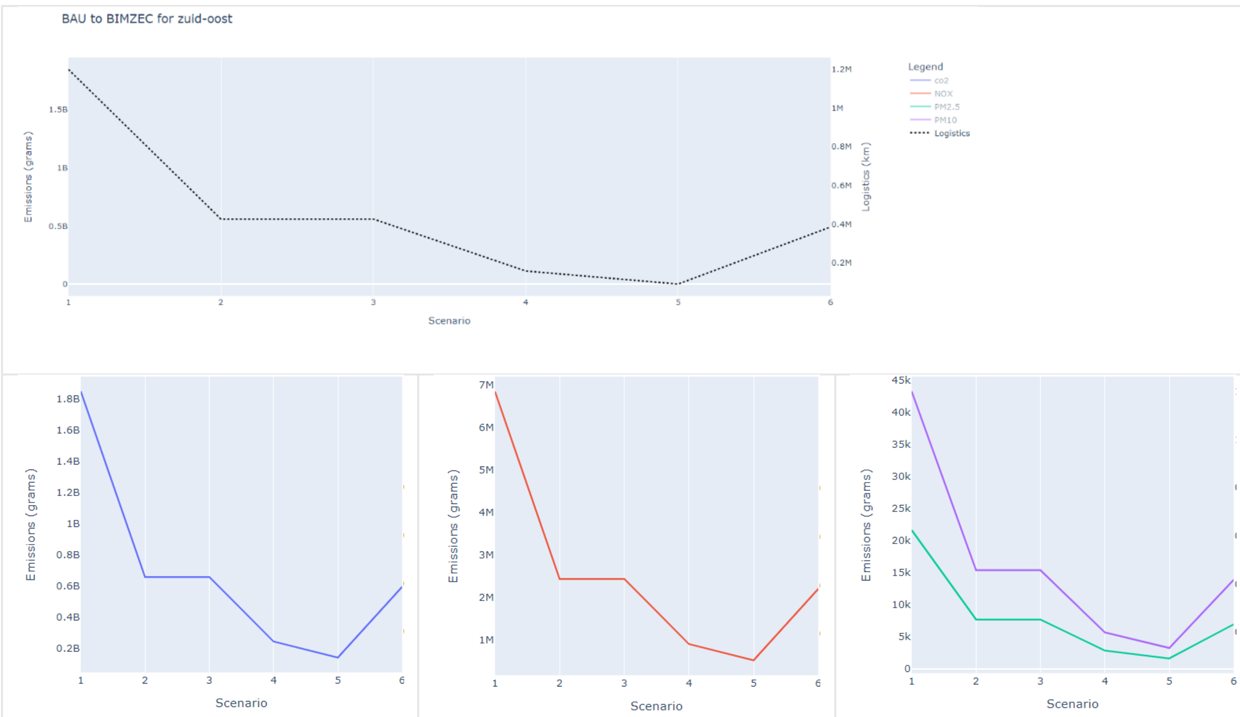
The table 6S below summarizes which parameters are changing when we are moving from one scenario to the next, and explains how these changed parameters affect the results of the model.

Supplementary Table 6: Incremental parameter changes between modeled scenarios

S	Parameter change	Explanation
1-2	+ hubs + water network	Hubs are added, and where possible, the water network is used. This leads to a drop in CO2 emissions, but an increase in NOX and PM emissions. While the number of transportation movements decreases with hubs, which lowers CO2; ships produce more PM and NOX than trucks, leading to higher NOX and PM overall.
2-3	+ semi-electric trucks	Trucks moving within the A10 highway in Amsterdam are now electric. This does not lead to a significant change in emissions, because most of the transportation movements (from suppliers to hubs) are outside of the A10, and therefore unaffected.
3-4	+ biobased buildings	Buildings are now built with biobased materials. This leads to a significant increase in emissions. This is because the supplier for timber is around 10 times further away than other suppliers. This is a surprising result and will be explained further in the section “interesting or unexpected findings” in this report.
4-5	+ electric trucks + modularity	All transportation movements within the AMA are electric, and buildings are now both biobased and modular. This leads to a large decrease in emissions, mostly thanks to the fact that the modules supplier is much closer than the timber supplier.
5-6	+ circularity	Buildings are now biobased, modular, and circular (where possible). This leads to a drop in emissions, as demolition sites are closer to suppliers, leading to less travel distances for vehicles.

Zuid-Oost case study

The model was applied to the Zuid-Oost district of Amsterdam to examine scenario-dependent differences in emissions and logistics movements at the district scale. The local municipality is considering building a construction hub in the area. We were invited by local policy makers to model the local impacts of building a construction hub in Zuid-Oost, focusing both on local emissions and transportation movements. The following shows the impact of the 6 scenarios, showing total emissions (CO2, NOX, PM2.5, PM10), and the total amount of logistics movements in km. The impacts are summarized for the study of Zuid-Oost.



CO2 emissions	NOX emissions	PM emissions

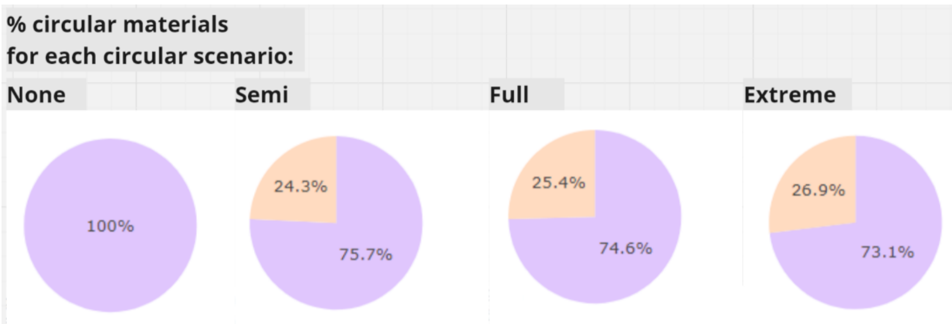
Supplementary Figure 4: Impacts (logistics movements, CO2, NOX, PM emissions) for Zuid-Oost

As seen in the figures above (Supplementary Figure 4), adding hubs (scenarios 1-2) leads to a significant drop in both emissions and transportation movements within the area. The drop in total logistics movements is from ~1.1 million km to ~420,000 km, a drop of more than 50%. Adding circular materials (scenarios 5-6) leads to a slight increase in emissions (140 million gCO2 to 600 million gCO2) and transportation movements (~90,000 to ~380,000 km). The other parts of the chart are similar to results for the whole model.

Additional figures and relevant findings

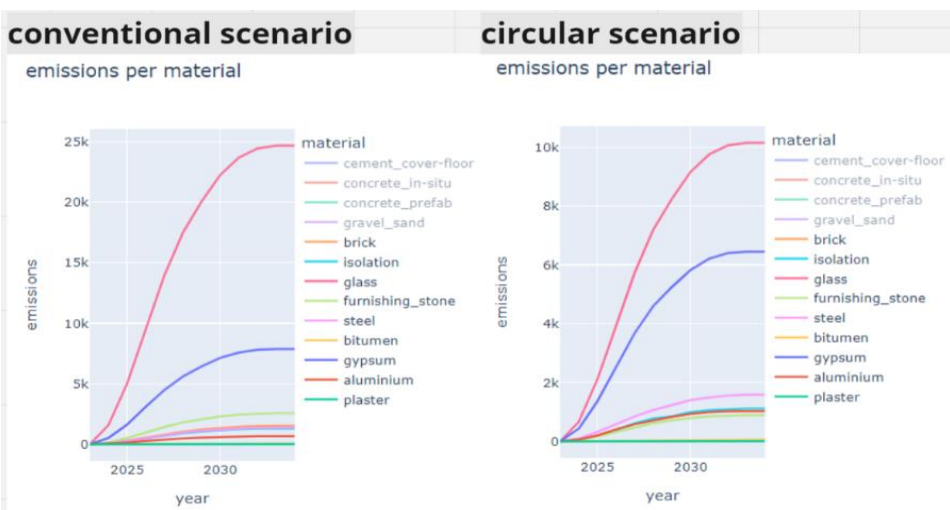
While simulating the different scenarios on the model, we found some interesting or unexpected findings. These are shows through additional figures below.

Circular material composition



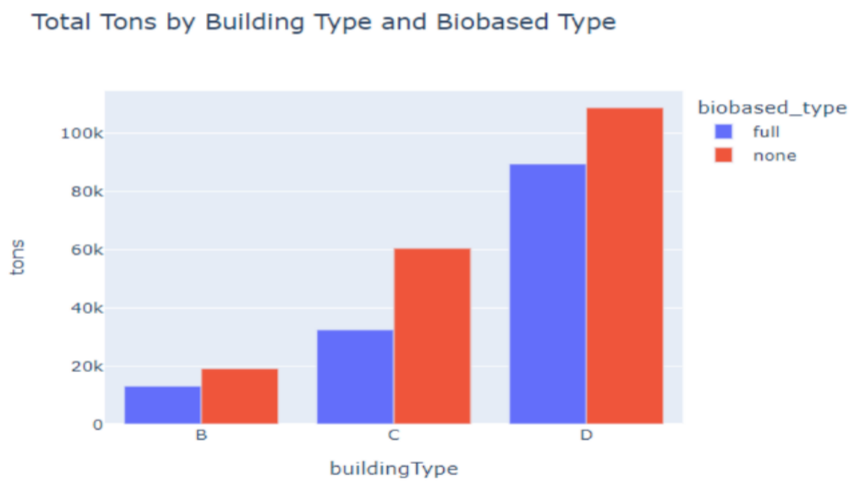
Supplementary Figure 5: It shows the share of circular materials by mass for each circularity scenario. Across the Semi, Full, and Extreme scenarios, the proportion of materials sourced from demolition sites remains below one third of total material demand; this is because most of these 'bulk' materials are not reused via hubs. Therefor the amount of circular materials ranged only from 24.3 - 26.9%. However, when we only look at the emissions associated with non-bulk materials, the emissions drop from conventional to circular scenario is more significant: around 60%.

Material-level emissions breakdown



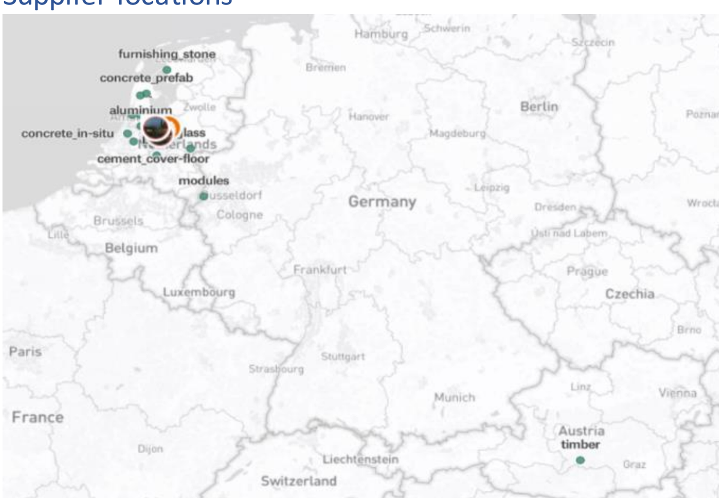
Supplementary Figure 6: It presents transportation-related emissions disaggregated by material type for the conventional and circular scenarios. The figure highlights differences in the relative contribution of individual materials to total emissions across scenarios.

Material mass by building and biobased type



Supplementary Figure 7: It reports total material mass by building type for conventional and biobased construction variants. Across all building types, biobased variants exhibit lower total material mass compared to conventional variants (biobased buildings are 10-50% lighter, depending on the building type).

Supplier locations



Supplementary Figure 8: It maps the locations of material suppliers and construction-related facilities used in the model. Supplier locations vary substantially in distance from the Amsterdam Metropolitan Area. As seen in the map, the supplier for timber is in Austria, which is 10 times further away from AMA compared to the other suppliers.