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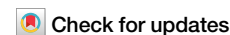
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# Spatial optimization of circular timber hubs



Tanya Tsui<sup>1</sup>✉, Titus Venverloo<sup>2</sup>, Tom Benson<sup>2</sup> & Fábio Duarte<sup>2</sup>

In the European Union, construction is responsible for 36% of CO<sub>2</sub> emissions and 40% energy consumption. The reuse of construction materials has been receiving increasing attention, including regulations established by the European Union, and cities establishing goals to reuse construction materials. This is the case for Amsterdam, which established the goal of reusing 50% of construction materials in new construction by 2030. Part of the challenge of reuse of construction materials in urban areas is to optimize the waste-to-resource loops: finding the optimal scale and location for circular construction hubs—facilities that collect, store, and redistribute construction waste as secondary construction materials. In this paper, we use the supply and demand of timber construction materials in Amsterdam as a case study to find the optimal scale and location for construction hubs. We used the spatial simulated annealing algorithm as an optimization method for balancing the trade-off between small and large-scale hubs, using cost-effectiveness to compare potential locations and identify the optimal solution. We found that the optimal number of hubs for our study area is 29, with an average service radius of 3 km. This study has implications for policymakers, urban planners, and companies seeking to implement circular economy principles.

Cities consume 60–80% of natural resources globally, produce around 50% of global waste and 75% of greenhouse gas emissions<sup>1</sup>. The situation might worsen, with the urban population expected to reach 6.5 billion by 2050, the equivalent of two-thirds of the future global population<sup>2</sup>. Reducing emissions and increasing resource efficiency is a major challenge for cities, and transitioning to a circular economy (CE) has been proposed by policymakers as a potential solution<sup>3</sup>. While there is no common definition for CE, it is generally understood as a closed-loop system that employs circular processes such as reuse, refurbishing, remanufacturing, and recycling to convert waste into secondary resources, to keep materials and products at their highest level of use for as long as possible<sup>4</sup>.

Since 2016, The Netherlands has aimed to achieve a fully circular economy by 2050<sup>5</sup>. In response to this goal, a number of Dutch municipalities and provinces have produced “circular city”<sup>6–9</sup> and “circular region”<sup>10,11</sup> strategic documents detailing how CE could be implemented at the city or regional level. However, these documents often focus on an urban governance perspective, discussing policy analysis and stakeholder management; rather than an urban planning perspective, understanding the spatial requirements and restrictions for a CE. In fact, when discussing the circular transition, the Dutch National Strategy on Spatial Planning and the Environment (Nationale

Omgevingsvisie - NOVI) states that, “the consequences of this (circular economy) transition on transport flows, use of space, the environment and security remain uncertain”<sup>12</sup>.

Dutch construction and demolition companies have responded to CE policy goals by starting circular construction hubs: facilities that collect, store, process, and redistribute construction waste to be reused as secondary construction materials<sup>13,14</sup>. A previous study on circular construction hubs in the Netherlands found that hubs vary in terms of their spatial scale of operations (regional versus local), and tend to deal with specific material types, such as wood, bulk materials, or building components<sup>13</sup>. However, locations and scales of hubs are arbitrarily chosen by individual companies, without a broader overview of the spatial impact of hubs on their surrounding region as a whole.

In recent years, researchers in industrial ecology, economic geography, and urban planning have highlighted the significance of spatial factors, such as proximity to industrial clusters and accessibility to secondary resources, as a key element in the study of circular cities, as these elements play an important role in the success of a CE<sup>15–18</sup>. Within this literature, a recurring question is the spatial scale of waste-to-resource flows, and whether resource loops should be closed at the local or global scale. This issue has been mostly explored by the fields of industrial symbiosis and waste management, where

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researchers have debated the benefits and trade-offs of organizing resource flows at the local, regional, national, or global scale.

Some studies have shown that material loops can be closed at the local scale, with resource exchange distances of around 2–5 km. Cases can be found in industrial symbiosis literature, where companies located in the same industrial park<sup>19,20</sup> or even the same facility<sup>21</sup> exchange resources such as electricity, heat, and organic waste. These findings are prominent in earlier industrial ecology literature, strengthened by the empirical findings on the Kalundborg Eco-industrial Park in Denmark - a seminal case study of industrial symbiosis<sup>19</sup>.

Other studies have shown the validity of closing material loops at the regional scale, with resource exchange distances of 30–50 km. An analysis of location data for industrial symbiosis partnerships in the United Kingdom found that the average distance between industrial symbiosis partners was 32.6 km<sup>22,23</sup>. Additionally, a study in Germany's Rhine-Neckar region concluded that the regional scale is large enough to provide a diverse enough group of industries and enough waste volumes that could allow for resilient and stable industrial symbiosis<sup>24</sup>. A spatial optimization study of concrete recycling plants in the Netherlands also resulted in facilities operating at the regional scale<sup>25</sup>.

Finally, studies have also argued for closing material loops at the global scale. The spatial scale of flows in the waste industry was largely determined by economic concerns - imbalances in supply and demand, transportation cost - which often lead to the decision to close loops globally<sup>26</sup>. In a study on Australia's metal industry<sup>27</sup>, researchers found that it was impossible to have a CE for metals in one country alone, as no country has the capacity to provide the full cycle of processes, including extraction, production, use, disposal, and recovery. A spatial optimization of the German food industry found that growing the majority of food in Brazil and transporting it back to Germany led to lower emissions than growing locally<sup>28</sup>, disputing the common assumption that the local scale leads to both environmental benefits.

As seen within existing literature, quantitative factors for determining the spatial scale of closing material loops include the value and weight of the material; and financial concerns of the operation, such as transportation costs or profit margins. Qualitative factors may include market maturity for CE, existing regulations, and well as knowledge and skills of the construction industry. From waste management literature, spatial scales seem to be determined by financial or logistical reasons. For example, the threshold for a recycling firm is the minimum volume of waste generated in an area at which a firm can profitably aggregate, process, and ship to a customer<sup>29</sup>. This means the location should be in an area with a high enough density of waste producers (municipal, commercial, industrial) to generate enough waste within an area that can be covered by their transportation costs.

From industrial symbiosis literature, more emphasis is placed on the feasibility of material reuse as a factor affecting the scale of closing material loops<sup>19,23,24</sup>. Materials that are difficult to reuse as a resource tend to travel longer distances, as it is more difficult to find a match between supply and demand close by. With increasing costs of land-filling, companies are also more willing to invest in long-distance travel for industrial symbiosis to avoid disposal costs.

We use the reuse of timber construction materials in the Amsterdam Metropolitan Area (MRA, Metropoolregio Amsterdam in Dutch) as a case study in finding the optimal scale of closing resource loops. The MRA has an area of more than 2500 square kilometers, consists of 30 municipalities, with a population of 2.5 million inhabitants. We chose the MRA as our case because of the region's combined policy goals in circular and timber construction. In 2021, the municipalities within the region signed a green deal on timber construction, aiming for 20% of new construction in the city to be made of timber by 2025, which corresponds to approximately 3000 timber constructed homes per year<sup>30</sup>. As of 2021, 7400 timber-framed homes were either being built or had won a tender. Additionally, the municipality of Amsterdam has set ambitious goals for transitioning to a CE since 2016<sup>31</sup>, aiming to use 50% less raw materials by 2030<sup>6</sup>. As of 2021, the extent of raw

material use in the Netherlands has hardly changed since 2010, although material efficiency has increased<sup>32</sup>.

The goal to increase timber construction in the MRA is driven by environmental benefits associated with building with timber. Timber is a renewable resource if forests are harvested responsibly. CO<sub>2</sub> is sequestered in trees as they grow, and when timber is used in construction, the carbon remains stored in the timber, effectively removing it from the atmosphere during the life of the building, or longer if the timber is reused. Timber also is well suited for reuse in circular construction, as it is light and easy to manipulate, making it well suited for dry, detachable connections<sup>33</sup>.

There are currently a small number of construction hubs in the region storing and exchanging timber. These hubs are currently operated by social organizations at a local scale, usually collecting materials from within 5–10 km<sup>13,14</sup>. As MRA's policy goals increase the demand for circular timber in the future, hubs will need to scale up accordingly as well. However, it is unclear how these hubs will scale up - will there be a small number of large-scale hubs operating at a regional scale, or a large number of small-scale hubs collectively covering the region, each operating at a local scale? Existing surveys of circular hubs have found that their spatial scale is determined by similar factors identified in waste management and industrial symbiosis literature, such as transportation, storage, and processing costs<sup>13,14</sup>, but these findings have not yet been verified using statistical methods.

While there is ample literature discussing the spatial scales of closing material loops, none have applied this knowledge to circular construction hubs. Moreover, most studies on spatial scale have surveyed existing companies and made conclusions based on the existing status quo, rather than imagining a future where CE is the norm. Consequently, very few studies have used spatial optimization to determine the optimal scale of material loops<sup>25,28</sup>. Finally, existing spatial optimization studies have neglected two important factors: land prices, and supply and demand matching. High land prices in central areas could increase storage costs, potentially pushing hubs to the periphery. If future demand for construction waste greatly exceeds supply, less space would be required to store materials before they are redistributed.

Since circular hubs are a relatively new phenomenon, the current understanding on suitable locations and scales is limited. Hub locations are currently chosen arbitrarily by individual companies, without a holistic understanding of their impact on the region as a whole. Without this top-down perspective, there is the risk of the region establishing the wrong number of hubs, or setting up hubs at the wrong scale, resulting in inefficiencies in terms of transportation emissions, material exchanges or operational costs.

The aim of this study is therefore to use spatial optimization methods to find the optimal scale and locations of circular timber hubs in the MRA. We aim to find a solution that balances the trade-offs between large and small-scale resource exchanges mentioned in existing literature - minimizing transportation distances with small-scale exchanges on one hand, while maximizing supply and demand matching with large-scale exchanges on the other<sup>23,24</sup>. We aim to add to existing literature on circular construction hubs by taking into account CO<sub>2</sub> reduction of timber reuse, land price, as well as supply and demand matching in the optimization model.

Spatial simulated annealing was used as an optimization algorithm to determine the optimal number and locations of circular timber hubs in the MRA for the study period of 2022–2026. Cost-effectiveness, measured in euros per tCO<sub>2</sub>eq reduction, was used in our algorithm to select the optimal solution. Costs (in euros) consisted of transportation and storage costs, while total emissions reductions (in tCO<sub>2</sub>eq) took into account transportation emissions and emissions reductions from timber reuse. The candidate hub locations were industrial sites in the study area with an environmental zoning category<sup>34</sup> of 2–3: industrial sites 30–100 km from quiet residential areas, and 0–50 km from mixed areas<sup>35</sup>. The locations of future supply and demand for secondary timber were taken from a scenario study of material stocks and flows of construction materials in the Netherlands<sup>36</sup>. The study uses locations of future demolition and construction sites to predict where and how much secondary construction materials will be supplied and

demanded from 2022 to 2050. A detailed description of the optimization algorithm, cost-effectiveness calculations, and data is supplied in the Methods section at the end of this paper.

## Results

Using the spatial simulated annealing optimization, the cost per tCO<sub>2</sub>eq reduction was calculated for a range of possible number of hubs in the MRA, from 1 to 135—which is the total number of industrial sites in the area. This resulted in a cost per tCO<sub>2</sub>eq reduction curve, where the x-axis represents the number of hubs, and the y-axis represents the cost per tCO<sub>2</sub>eq reduction (Fig. 1). We found that placing 29 hubs in the study area resulted in the lowest cumulative cost per tCO<sub>2</sub>eq reduction, although the value remains consistently low for 20 to 40 hubs, at around 45–46 euros / tCO<sub>2</sub>eq reduction. When compared to sub-optimal hub numbers, the optimal number of hubs (29) allows for a total cost reduction of 21.3 million euros and a total CO<sub>2</sub>eq reduction of 499 kilo tons, which is 94.6% of the maximum tCO<sub>2</sub>eq reduction possible for the MRA.

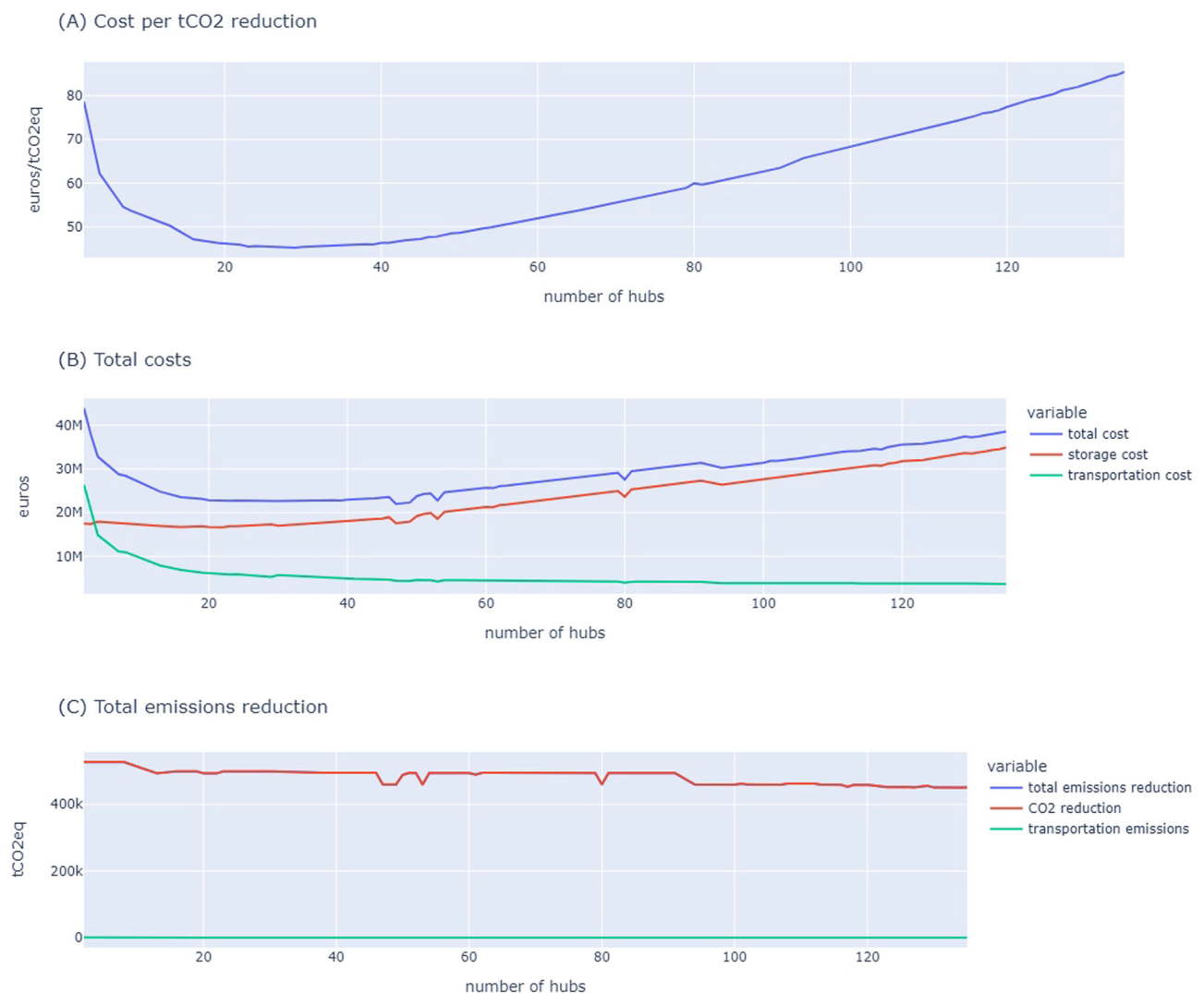
The service radii of circular timber hubs ranged from around 1 km to 23 km, with an optimal average service radius of 3 km, at 29 hubs (Fig. 2). Service areas for each hub vary – areas with higher material density (e.g. in Amsterdam city center) tend to have hubs with smaller service areas. This could be because areas of higher material density are often urban centers,

and tend to have higher rental prices, making it more cost-efficient to construct smaller hubs as a strategy to reduce storage costs.

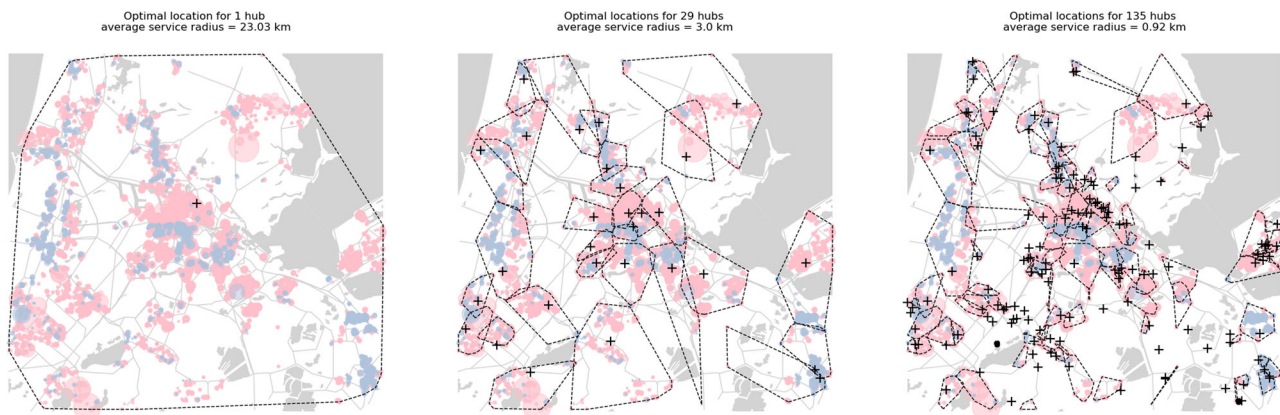
Our model resulted in optimal hub locations for 135 scenarios, with the number of hubs ranging from 1–135. We overlapped all 135 scenarios and counted, for each industrial site, how many times it was chosen by the optimization algorithm as an optimal location, and found that some industrial sites were more frequently chosen than others (Fig. 3). These locations can therefore be considered as potential key future locations for circular timber hubs. Since construction hubs are currently built by individual companies or communities without any top-down coordination, it may be difficult for the Dutch government to control the exact number of timber hubs built. If this were the case, focusing on these key future locations may be even more important for policy decisions than the exact ‘optimal’ number and locations of hubs. There were also industrial sites that were never selected for any of the hub numbers (gray dots in Fig. 3). These locations are therefore less important for the creation of circular timber hubs, and could be prioritized for other functions.

## Discussion

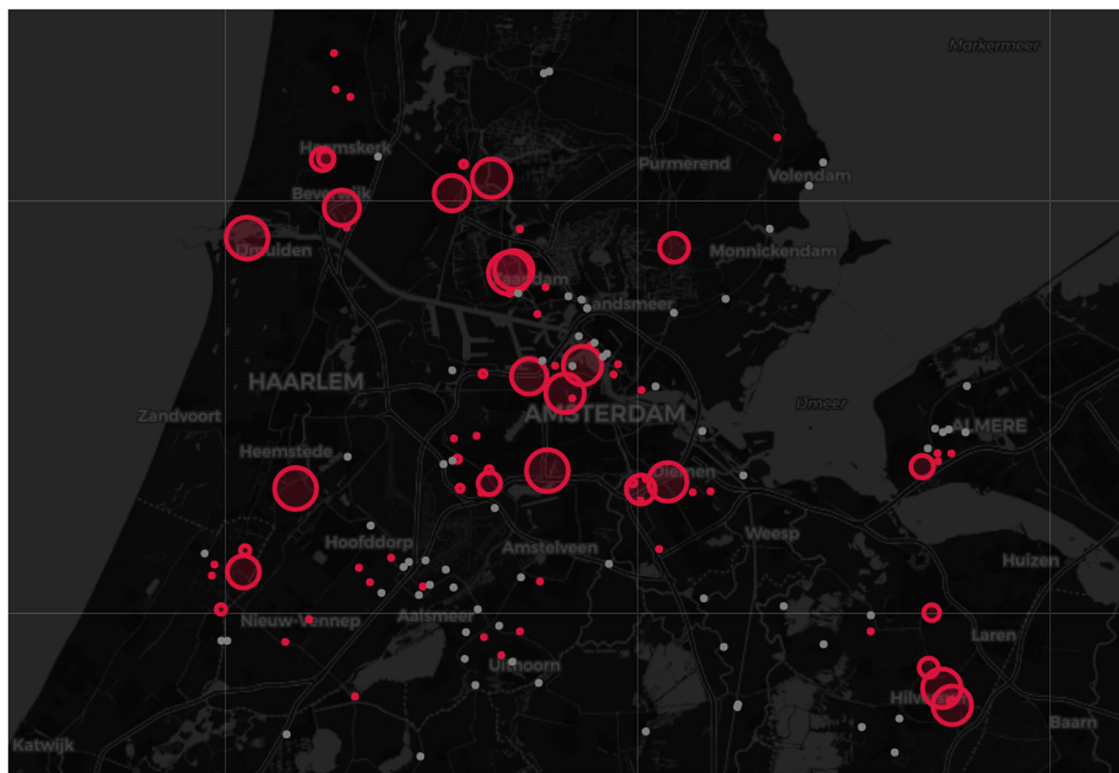
The cost per tCO<sub>2</sub>eq reduction curve shows that the cost rapidly decreases as the number of hubs goes from 2–20, remains relatively constant from 20–40 hubs, then increases steadily from 40 hubs onwards (Fig. 1). When the number of hubs is lower (nHubs = 2–20), cost / tCO<sub>2</sub>eq reduction decreases



**Fig. 1 | Summary of results.** Line charts showing changes in **A** cost per tCO<sub>2</sub> reduction, **B** total costs, and **C** total emissions reductions as number of hubs increases. For chart C, the line for “total emissions reduction” (in blue) is hidden behind the line for “CO<sub>2</sub> reduction” (in red), because the two values are very similar.



**Fig. 2 | Optimal locations and service areas for 1, 29, and 135 hubs.** Black crosses = hub locations, black dotted lines = service areas, blue dots = timber supply, pink dots = timber demand, gray lines = road network.



**Fig. 3 | Popularity of candidate hub locations.** Circle size represents the number of times the location has been chosen as an optimal location. Red dots are locations that were chosen at least once, gray dots are locations that were never chosen.

when more hubs are added. This is because, at these hub numbers, adding more hubs decreases the transportation cost rapidly. When the number of hubs is roughly between 20–40, cost/tCO<sub>2</sub>e remains roughly constant because all the components (transportation cost and emissions, storage cost, and CO<sub>2</sub>e reductions) remain roughly the same when more hubs are added. When the number of hubs goes above ~40, cost/tCO<sub>2</sub>e increases steadily mainly due to storage costs. As more hubs are added to the city, some hubs start to become redundant—they are barely storing any materials (or not storing any materials at all), but still using up space, resulting in unnecessary high rent and building costs (Fig. 4).

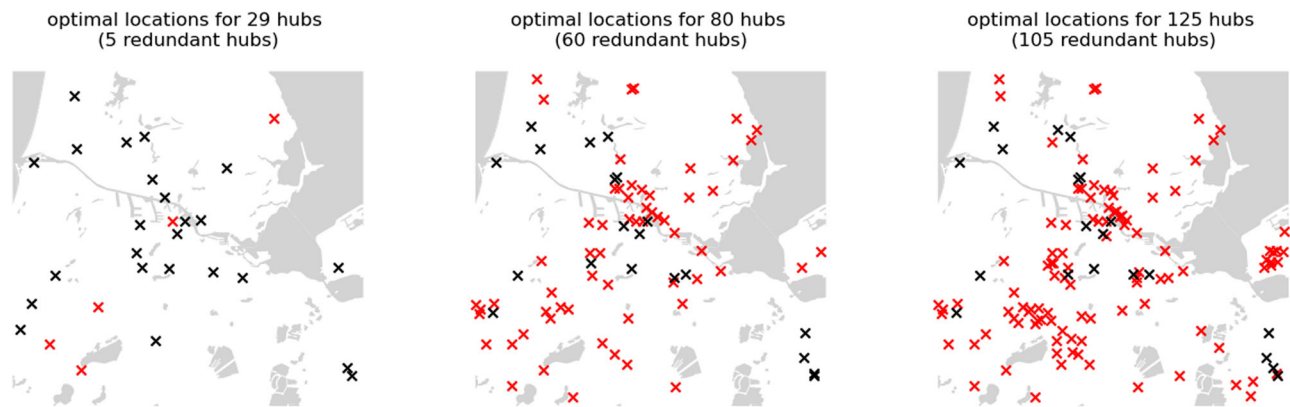
Each of the four components of the cost/tCO<sub>2</sub>e calculation has a different effect on the final cost curve. Transportation costs affect the curve at nHubs = 2–20 — it accounts for the rapid decrease in price when more hubs are added. The transportation cost seems to decrease exponentially as

the number of hubs increases. For lower hub numbers, adding an extra hub decreases the transportation cost significantly, whereas at higher hub numbers, adding an extra hub only has a minor impact.

Storage costs affect the curve starting nHubs = 40. Here, redundant hubs start to appear when more hubs are added, which increase rent and building costs unnecessarily. The increase in storage costs from adding redundant hubs follows a linear trend.

CO<sub>2</sub>e emission reductions do not have a large effect on the curve — adding more hubs does not make a significant difference in reducing CO<sub>2</sub>e emissions. While there is a slight decrease in CO<sub>2</sub>e reductions as the number of hubs increase, the change is not as large as the changes in transportation and storage costs. This is because the future demand of timber far exceeds the future supply in the MRA — within the study period of 2022 to 2027, the total future timber demand is around 710,000 tons, while





**Fig. 4 | Redundant hubs for solutions with 30, 80, and 125 hubs.** Black crosses = functioning hubs, red crosses = redundant hubs.

the future timber supply is only around 350,000 tons. This excess demand guarantees that most of the secondary timber is reused regardless of hub size. Finally, transportation emissions do not have an effect on the curve, because the values are much lower than CO<sub>2</sub>eq reduction from timber reuse.

The results in this section indicate a number of recommendations for planning circular timber hubs in the MRA. As mentioned in the introduction section, circular hubs currently processing timber are usually operated by communities at the local scale. However, when demand for circular timber increases in the future, timber hubs will need to scale up accordingly as well. According to our results, the average service radius of circular timber hubs should be around 3 km, which is similar to the service area of existing timber hubs. We, therefore, recommend the MRA to increase the total number of hubs but keep each of the hubs operating at the local scale. This would be an alternative to increasing the scale of the existing hubs, resulting in a few large-scale hubs covering the entire region.

Policies encouraging the establishment of circular hubs should ensure that there are no more than 40 timber hubs established in the MRA at one time, as more hubs lead to redundancy. This is especially important given the scarcity of land in the MRA - policy needs to balance spatial needs for circularity with other priorities, such as housing, health, energy, or biodiversity<sup>37</sup>.

The optimal number of hubs were constrained by transportation and storage costs, rather than emissions associated with transportation and material reuse. This suggests that, for the MRA, the argument for optimizing circular timber hubs is not reducing emissions, but rather reducing costs. The amount of emissions reductions in the region would have been similar regardless of the number of hubs, but the optimal number of hubs we identified (29) would be the cheapest solution.

The constraints of costs versus emissions would look different for other cities, due to different density, morphology, and building types. For example, other cities with less land scarcity would have lower land prices, resulting in a smaller effect of storage costs on the optimization curve. The constraints could also look different for other materials, as they have different cost and emissions calculations. For example, optimizing concrete recycling plants would take into account emissions from recycling machinery<sup>35</sup>. Finally, expanding the study to a larger area (the whole country for example) could also lead to a different optimal hub scale. In this case, hubs may benefit from settling in the periphery of urban areas, where land is cheap but materials are still close by.

This study has a number of limitations and shows the difficulty of making spatial planning decisions solely based on a mathematical model. Like all urban areas, the MRA is a complex system, containing dynamics that cannot be fully captured in one study. These dynamics may include future changes in infrastructure and land use, emerging waste processing technologies, and changing public opinions, stakeholder interests, or environmental laws. The results of this study should therefore not directly lead to policy decisions but rather be seen as insights informing policymakers.

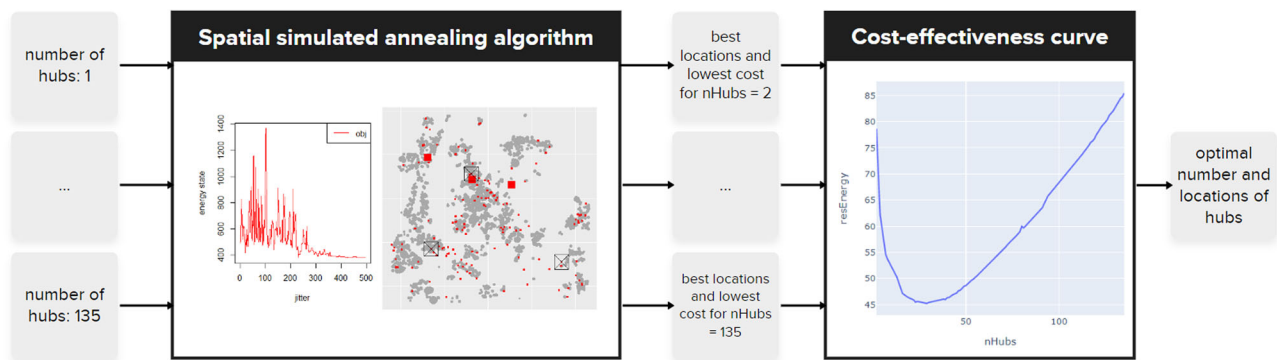
While the data set on future supply and demand of timber has predictions from 2022 to 2050, we chose a shorter study period of the optimization algorithm – 2022–2026. With this choice, we assume that hubs will not be permanent, but will rather change locations approximately every 5 years depending on future locations of construction and demolition sites. Currently, circular hubs are often simple storage structures that can be disassembled and reassembled with minimal environmental impact. Therefore, we assume that the transportation emissions savings from changing hub locations every 5 years would outweigh emissions for dis- and re-assembling the facility.

Materials from demolition sites are highly homogenous. While the dataset categorized materials by type (such as concrete, glass, and timber), it does not make finer distinctions within each material type. This means there is no way of knowing what type of timber (structural, facade, interior wall) is arising from the demolition sites. Therefore, in reality, there could be less supply and demand matching than represented in the model, due to a mismatch between building component types. A more accurate model would require a materials dataset that makes a component-level distinction for each material type - a task yet to be achieved in existing literature.

We assumed that the oldest 16% of buildings (excluding heritage sites) in the future material supply and demand dataset would be demolished, as older buildings will more likely be demolished first, and 5 years is 16% of the study period of the original dataset (30 years). However, demolitions are not evenly distributed in time and space. In reality, demolition sites could be clustered in a certain area, or during a certain time period. Because there is no exact data on when demolitions will occur, this spatial or temporal clustering is not reflected in the model.

This study is also limited to the MRA, which has a unique set of spatial concerns - it is an urbanized and dense region with high land scarcity and real estate costs, as well as ambitious goals for circular and timber construction. The optimal number of hubs could vary significantly in other cities either due to the geographic area, real estate costs, or policies related to the reuse of construction materials. For example, another region could benefit from larger hubs to ensure supply and demand matching, either because it has less ambitions for timber construction (and therefore less future demand for timber), or because it is less densely built, requiring hubs to travel further to collect and redistribute materials.

The optimization algorithm assumes that hubs provide full coverage to all future supply and demand locations for secondary timber. In other words, the hubs in the algorithm behave like post offices, which collectively cover all possible clients; rather than like chain stores, which only aims to maximize the coverage of most, but not all, clients. It was also assumed that the hubs work independently and do not communicate or share resources with each other, as this is the case for currently established circular hubs. However, there could be other models for organizing hubs. For example, hubs could be organized in a hierarchical network with central hubs aggregating and sorting materials from more peripheral hubs. In this case,



**Fig. 5 | Diagram showing overall methodology.** We iterated through a range of hubs from 1 to 135 and found the best hub locations for each iteration. The cost-effectiveness of the best locations for each iteration was plotted on a cost-

effectiveness curve. The lowest point of the curve indicated the optimal number of circular timber hubs for the MRA.

the optimization could result in 1–2 large scale hubs for the whole region, each connecting to a number of smaller hubs that operate at a local scale (3 km). These variations, aligned with management studies, were not a research topic in this paper.

For the calculation of cost / tCO<sub>2</sub>eq reduction, a number of assumptions were made based on existing studies on circular construction hubs<sup>14,38</sup>. Changing these assumptions could have an impact on the results. This is especially true for the calculation of storage costs and tCO<sub>2</sub>eq reduction, as these parameters are based on more assumptions than transportation costs and emissions. For more details please refer to the methods section.

In terms of theoretical contributions, this study takes into account supply and demand matching when optimizing for spatial scale of resource reuse, thanks to a novel predictive data set<sup>36</sup>. Matching future supply and demand of secondary materials is important for CE research, because it is essential to quantify the possibilities and limitations of resource reuse. As seen in the dataset for future supply and demand for construction materials, future demand for timber, 710,000 tons, is more than double of future supply, 350,000 tons. It is therefore impossible to completely satisfy future demand for timber construction materials with secondary timber from demolitions sites.

Additionally, while industrial ecologists have produced increasingly accurate datasets predicting locations of future supply and demand of materials, a connection to spatial planning has not yet been made. By using a predictive dataset for the Netherlands to calculate the optimal number and locations of circular timber hubs in the MRA, this study provides an example of using results from industrial ecology to provide practical spatial planning recommendations.

In terms of practical contributions, this study presented the optimal number and locations for circular timber hubs in the MRA, as well as industrial sites that should be prioritized as locations of timber storage and exchange. We provided a concrete vision of how circular timber hubs might be established in a future where circular timber construction is the norm: around 30 hubs in total across the region, congregating around dense urban areas, each working at a local scale of approximately 3 km.

Our results also illustrate the important role governments can play in planning for a CE: If the establishment of circular hubs were completely market-driven with no governmental intervention, it would lack a top-down understanding of the collective economic and environmental impact of all the circular hubs working together as a whole. The results of this study can therefore show that, when given the right information, policymakers can provide insights that cannot be obtained by individual companies alone. Consequently, governmental organizations, such as municipal and provincial bodies, could use our results to prioritize industrial sites for establishing circular hubs, or use incentives and regulations to regulate the scale and locations of hubs in the region.

## Methods

### Overview

We aimed to identify the optimal spatial scale for circular timber hubs in the MRA using a mathematical optimization method spatial simulated annealing. The optimal scale was defined as a scale that is most cost-effective, minimizing costs and maximizing emissions reductions through timber reuse. In order to determine the optimal number and locations of hubs, we iterated through a range of possible numbers of hubs. For each iteration, an optimization algorithm was used to determine the optimal hub locations, as well as their cost-effectiveness value. The number of hubs with the lowest cost-effectiveness value was determined as the optimal number of hubs. The diagram below (Fig. 5) summarizes the overall methodology.

### Spatial simulated annealing

We chose between two basic strategies for solving spatial optimisation problems: exact and heuristic methods. Exact methods involve solving mathematical models to solve a problem, while heuristic methods use approximate algorithms that provide good solutions in a reasonable amount of time, but do not guarantee finding the optimal solution. Exact methods guarantee finding the optimal solution but can be computationally intensive, while heuristic methods provide approximate solutions quickly, even for large-scale problems<sup>39</sup>. Given a large number of possible combinations of locations for circular timber hubs, heuristic methods were chosen to optimize their number and location.

Spatial simulated annealing was chosen as a heuristic optimization method for this study for its effectiveness in finding good solutions for complex problems within a large search space<sup>40,41</sup>. The method is inspired by the process of slow cooling in metallurgy. The algorithm begins by exploring the solution space broadly, accepting both improvements and occasional steps backward (worse solutions) to avoid local optima. As the number of iterations increases, the probability of accepting worse solutions is reduced, leading the search to converge more tightly around the best solutions found.

### Optimization objective: cost-effectiveness

The objective of the algorithm, represented below by Eq. (1), is to choose a combination of hub locations that are most cost-effective – that minimizes costs and maximizes CO<sub>2</sub>eq emission reductions through timber reuse.

$$C_{\text{eff}} = (C_{\text{stor}} + C_{\text{trans}}) / (R_{\text{CO}_2\text{eq}} - E_{\text{trans}}) \quad (1)$$

Where:

$C_{\text{eff}}$  = cost effectiveness (euros per tCO<sub>2</sub>eq reduction)

$C_{\text{stor}}$  = storage cost (euros)

$C_{\text{trans}}$  = transportation cost (euros)

$R_{\text{CO}_2\text{eq}}$  = CO<sub>2</sub>eq reduction from timber reuse (tCO<sub>2</sub>eq)

$E_{\text{trans}}$  = transportation emissions (tCO<sub>2</sub>eq)

Cost-effectiveness is an indicator used in sustainability research that compares the costs and benefits of different sustainable interventions<sup>42,43</sup>. It takes into account the costs of implementing a particular intervention, as well as the expected environmental benefits, identifying interventions that can achieve the greatest impact for a given level of investment. For our case, the cost effectiveness value represents the collective impact of all chosen hubs within a potential solution, rather than a single hub.

In order to determine the optimal number and locations of hubs, we iterated through a range of possible numbers of hubs: 1–135, which is the total number of industrial sites in the area. For each iteration, the spatial simulated annealing algorithm was used to determine the optimal hub locations, as well as their cost / tCO<sub>2</sub>eq reduction value. The number of hubs with the lowest cost-effectiveness value was determined as the optimal number of hubs.

### Cost-effectiveness: contributing factors

The factors contributing to cost effectiveness - storage cost, transportation cost, CO<sub>2</sub>eq reduction, and transportation emissions, are explained below. For more details see the supplementary information document and programming scripts.

**Storage cost.** The calculation of storage cost is expressed in Eq. (2). To calculate the storage area, we assumed that the average storage time of timber is six months<sup>38</sup>, and that secondary timber will only be stored if there is demand for it within the same service area. The building price, 382.51 euros per square meter, was based on data collected by Statistics Netherlands on building costs of halls, sheds, greenhouses, and stables<sup>44</sup>. The rental price, which varies at each location, was based on governmental data on industrial sites in the Netherlands<sup>35</sup>.

$$C_{\text{stor}} = \sum_{i=1}^n a_{\text{stor}} (p_{\text{build}} + p_{\text{rent}}) \quad (2)$$

Where:

$C_{\text{stor}}$  = storage cost (euros)  
 $a_{\text{stor}}$  = storage area (sqm)  
 $p_{\text{build}}$  = building price per square meter (euros per sqm)  
 $p_{\text{rent}}$  = rental price per square meter (euros per sqm)

**Transportation cost.** The calculation of transportation cost is expressed below in Eq. (3). We assumed that secondary timber is transported from supply locations (demolition sites) to the hub to be stored. Then, the secondary timber is transported from the hub to the demand locations (construction sites) to be reused. The price for transporting one ton of timber for one kilometer was based on governmental data on freight transport in the Netherlands<sup>45</sup>.

$$C_{\text{trans}} = p_{\text{trans}} * \sum_{i=1}^n d_{\text{SH}} * t_{\text{s}} + d_{\text{HD}} * t_{\text{D}} \quad (3)$$

Where:

$C_{\text{trans}}$  = transportation cost (euros)  
 $p_{\text{trans}}$  = price for transporting one ton of timber for one kilometer (euros)  
 $d_{\text{SH}}$  = transportation distance from supply location (S) to hub location (H)  
 $t_{\text{s}}$  = tons of timber at a specific supply location (S)  
 $d_{\text{HD}}$  = transportation distance from hub location (H) to demand location (D)  
 $t_{\text{D}}$  = tons of timber at a specific demand location (D)

**Transportation emissions.** Transportation emissions were calculated using a similar method as transportation costs, expressed below in Eq. (4).

The emissions associated with transporting timber were based on a life cycle analysis for road transportation in Europe<sup>46</sup>.

$$E_{\text{trans}} = e_{\text{trans}} * \sum_{i=1}^n d_{\text{SH}} * t_{\text{s}} + d_{\text{HD}} * t_{\text{D}} \quad (4)$$

Where:

$E_{\text{trans}}$  = transportation emissions (tCO<sub>2</sub>eq)  
 $e_{\text{trans}}$  = transportation emissions associated with transporting 1 ton of timber for 1 km (tCO<sub>2</sub>eq)  
 $d_{\text{SH}}$  = transportation distance from supply location (S) to hub location (H)  
 $t_{\text{s}}$  = tons of timber at a specific supply location (S)  
 $d_{\text{HD}}$  = transportation distance from hub location (H) to demand location (D)  
 $t_{\text{D}}$  = tons of timber at a specific demand location (D)

**CO<sub>2</sub>eq reduction.** The CO<sub>2</sub>eq reduction from timber reuse is expressed below in Eq. (5). The value is the amount of CO<sub>2</sub>eq emissions avoided if future timber demand were satisfied by secondary sources (timber waste) rather than primary sources (timber from sustainable forests).

We assumed that when timber demand is satisfied from primary sources, timber waste is incinerated, releasing emissions into the atmosphere. For secondary sources, we assumed that waste timber is stored in the nearest circular hub and reused as secondary timber by a construction site within the same service area. If there is an over-supply of waste timber, the excess is incinerated. The CO<sub>2</sub>eq emissions for this scenario are emissions associated with incinerating excess waste timber that was not reused.

$$E_{\text{CO2eq}} = \sum_{i=1}^n e_{\text{t}} * m_{\text{p}} - e_{\text{t}} * m_{\text{s}} \quad (5)$$

Where:

$E_{\text{CO2eq}}$  = CO<sub>2</sub>eq reduction from timber reuse (tCO<sub>2</sub>eq)  
 $e_{\text{t}}$  = tCO<sub>2</sub>eq emissions associated with incinerating one ton of timber (tCO<sub>2</sub>eq)  
 $m_{\text{p}}$  = amount of waste timber to be incinerated if no timber was reused (tons)  
 $m_{\text{s}}$  = amount of waste timber to be incinerated if there is timber reuse (tons)

### Constraining conditions: locations of hubs, supply, and demand

The constraining conditions for the spatial optimization were the candidate hub locations, and future supply and demand locations for secondary timber. The candidate hub locations were industrial sites within the MRA with an environmental category<sup>34</sup> of 2–3. Environmental category 2–3 refers to industrial sites that are 30–100 km from quiet residential areas, and 0–50 km from mixed areas. These conditions were chosen based on existing research findings on the spatial requirements for circular hubs in the Netherlands<sup>13,14</sup>. Industrial sites' locations, environmental categories, and rental prices were obtained from a governmental dataset<sup>35</sup>.

Future supply and demand locations for secondary timber were based on a dataset predicting the supply and demand for secondary construction materials in the Netherlands from 2022 to 2050, mapped onto a spatial grid with a resolution of 100 × 100 m<sup>36</sup>. To fit the conditions of this study, we filtered the dataset to only include timber supply and demand for our study period – 2022 to 2026.

To filter for future supply locations, we needed to determine which areas will most likely be demolished within our study period. First, grid cells with an average building age of older than 100 years were eliminated, as these were likely heritage areas. Then, the oldest 16% of the remaining grid cells were chosen, as older buildings will more likely be demolished first, and 5 years is 16% of the study period of the original dataset (30 years).

To filter for future demand locations, two steps were taken. First, 16% of grid cells were randomly chosen to represent demand during the study



period. Cells were chosen randomly because the dataset has no information on when future demand will occur. Then, a further 50% of grid cells were randomly chosen, as the municipality of Amsterdam's circular strategy aims to be 50% circular by 2030<sup>6</sup>.

The process of extracting, cleaning, and analyzing the data were written in the programming languages Python and R. The R package "spsann" was used to create the spatial simulated annealing algorithm<sup>47</sup>. Due to the high computational demand required by the spatial simulated annealing algorithm, the code was run on a Linux-based high-performance computing system provided by the Delft University of Technology, Delft Blue<sup>48</sup>. The programming scripts are in a GitHub repository.

## Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

## Data availability

The data that support the findings of this study are available from The Netherlands Environmental Assessment Agency (PBL), but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. The data are, however, available from the authors upon reasonable request and with the permission of The Netherlands Environmental Assessment Agency (PBL).

## Code availability

All code associated with this study is openly available and can be accessed at the following GitHub repository: <https://github.com/TanyaTsui/spatialOptimizationCircularHubs>.

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## Author contributions

All authors contributed to the design and execution of this project and reviewed and edited the manuscript. T.T. conceptualized the research design, acquired the data, conducted the spatial optimization, and wrote the first draft of the manuscript. F.D., T.V., and T.B. contributed to conceptualization, methodological development, and editing of the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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