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DOI
10.1007/s43615-023-00285-y

Publication date
2024

Document Version
Final published version

Published in
Circular Economy and Sustainability

Circular Economy and Sustainability (2024) 4:317–338
https://doi.org/10.1007/s43615-023-00285-y

ORIGINAL PAPER

Spatial Parameters for Circular Construction Hubs: Location Criteria for a Circular Built Environment

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Received: 10 November 2022 / Accepted: 14 June 2023 / Published online: 11 July 2023

Abstract
Implementing a circular economy in cities has been proposed by policy makers as a potential solution for achieving sustainability in the construction sector. One strategy that has gained interest by both policy makers and companies is to develop "circular construction hubs": locations that collect, store, and redistribute waste as secondary resources. However, there is limited literature taking a spatially explicit view, identifying the spatial parameters that could affect the locations of hubs both for now and in the future. This study therefore aims to categorize different types of circular hubs for the construction industry, collect spatial parameters required for finding suitable locations for each type of circular hub, and translate the spatial parameters into a list of data and spatial analysis methods that could be used to identify potential future locations. The study used the Netherlands as a case study, extracting spatial parameters from two sources: Dutch governmental policy documents on circular economy and spatial development and interviews with companies operating circular hubs. Four types of circular construction hubs were identified: urban mining hubs, industry hubs, local material banks, and craft centers. The spatial parameters were extracted for each type of hub from four perspectives: resources (such as material type, business model), accessibility (such as mode and scale of transportation), land use (such as plot size, land use), and socio-economic (such as labor availability). The parameters were then translated into a list of spatial data and analysis methods required to identify future locations of circular construction hubs.

Keywords Circular cities · Circular construction hub · GIS · Territorializing circular economy · Urban mining · Site selection analysis

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Introduction

The construction sector has a significant environmental impact in terms of waste production and resource use. Over the last century, while global population increased by a factor of ~ 4, usage of construction materials increased by a factor of ~ 42 [1]. The construction sector consumes the largest share of materials globally [2–4], and this consumption is expected to further increase in the future [5].

Since 2015, transitioning to a circular economy (CE) has been proposed by policy makers in the European Commission as a potential solution to sustainability [6]. Although there is no consensus on its definition [7], a commonly adopted notion of CE is keeping materials and products performing at their highest application level for as long as possible, while reducing environmental impacts and being aware of environmental trade-offs. CE has also been put forward as an alternative economic paradigm that stays within planetary boundaries and is socially just [8].

CE concepts were first applied to industrial sectors, but more recently, the importance of applying circularity to the built environment has been recognized by researchers and policy makers alike [9]. In the Netherlands, CE concepts have been integrated into governmental policy in the form of a national strategy, where construction and demolition materials have been highlighted in a specific transition agenda for a circular construction economy ("Transitieagenda Circulaire Bouweconomie") [10].

Within circular built environment research, the application of CE concepts has expanded from building materials and products to larger spatial scales, to include cities and regions. Much of these efforts fall under the topic of "circular cities" [11], and take the perspectives of urban governance, which studies the circularity of a city's policies and stakeholders [12–14] and urban metabolism, which studies the material, water, or energy flows of cities or regions [15–17]. While existing research explores circular cities from a governance and resources perspective, the spatial or territorial implications of a circular economy still remain broadly unexplored [18–20].

Circular cities research has started to inform Dutch policy, initiating circular strategy documents at the national [10], provincial [21–23], and municipal level [24–26]. Moreover, circular cities thinking have been implemented in spatial strategies at the national [27], provincial [28], and municipal level [29] as well.

One frequently mentioned idea in Dutch circular economy and spatial strategy documents are "circular hubs," often for the construction sector—locations where clusters of circular companies can gather to exchange resources and knowledge, or where waste can be stored, processed, and re-distributed as secondary resources. This triggered a number of companies to start circular hubs of their own, operating mainly within the demolition sector. While there seems to be a lot of interest in circular (construction) hubs, this new phenomenon is not well studied or defined in academic literature. There is very limited understanding of where the future locations of these hubs could be, or what spatial factors would determine these locations.

This study therefore aims to collect the spatial parameters that could determine the future locations of circular construction hubs in the Netherlands. Additionally, we aim to derive, from the spatial parameters, the data and spatial analysis methods that would be required to identify suitable circular hub locations. This study will therefore answer the research question, "What are the spatial parameters for locating circular construction hubs in the Netherlands?".

Using the construction sector in the Netherlands as a case study, this study will conduct a document review of Dutch policy documents on spatial and circular economy strategies, as well as semi-structured interviews with circular construction companies, including building material banks, construction logistics centers, and industrial estates.

From the document review and interviews, we identified four types of circular construction hubs, which varied in spatial scale and focus on logistics versus industrial activity. These types are urban mining hubs, industry hubs, craft centers, and local material banks. Spatial parameters were identified for each hub type, and categorized into four perspectives: resource, accessibility, land use, and socio-economic.

Theoretical Background

In recent years, researchers from the fields of industrial ecology, economic geography, and urban planning have started to advocate for the importance of space as a major factor in the study of the CE [18, 19, 30, 31]. Although the implementation of CE solutions have an obvious spatial expression, the spatial parameters of CE remain broadly unexplored. A spatial understanding of CE is important, because many CE activities require spatial factors such as agglomeration and accessibility to succeed. For example, circular companies may need to be close to larger industrial clusters, or be highly accessible to sources of secondary products or materials [19].

Researchers have identified a number of disciplines that use a spatial perspective to study CE and related topics such as urban metabolism and industrial symbiosis [19], identifies six territorial factors for CE: land-based, agglomeration, hard territorial factors, access to technology, knowledge-related factors, and governance, and [18] identified five spatial approaches to urban metabolism: political, territorial-economic, socio-ecological, governance and planning, and spatially explicit modeling.

Within spatially explicit circular economy research, two major perspectives study material stocks and flows: industrial clustering and urban mining. The study of industrial clustering examines the potential economic and environmental benefits of clustering companies together in order to share and exchange resources, infrastructure, or knowledge. This is studied mostly by industrial symbiosis literature, which studies the methods and factors that allow clusters of industrial facilities to successfully gain financial and environmental benefits from exchanging and sharing resources. The benefits of industrial proximity and co-location within industrial symbiosis literature are borrowed from the study of agglomeration economies within the discipline of economic geography [32, 33].

Agglomeration theory proposes that clusters of businesses in close proximity to one another create additional benefits that would not have occurred if those businesses were far apart [34–37]. These benefits were understood as economies of scale achieved from external factors, and could be categorized as localization and urbanization economies. In localization economies, most companies belong to the same industry, and generally use similar resources and generate similar products, co-products, by-products, and waste. This gives opportunity for more efficient management of common resources. In urbanization economies, companies belong to different industries, which gives opportunities for firms to exchange their large variety of inputs and outputs. Similar ideas on the benefits of agglomeration have also been introduced in gray literature, under the concepts of “zero waste industrial hubs,” “hubs for circularity” [38], and “circular city ports” [39].

Industrial symbiosis researchers have also started to study the spatial constraints of material exchanges, understanding that transportation distance of materials could depend on the material type and value, as well as company diversity in the local area [40–42]. Some studies have also tried to define the "optimal" scale for industrial symbiosis from these spatial constraints [43–45].

The urban mining perspective, on the other hand, estimates the availability of secondary resources in cities and countries by mapping the location of material stocks and flows within a given geographical area. Often, these studies use cadastre data (governmental recording of real estate properties) to estimate the amount of material potentially available. This is done by categorizing buildings into different archetypes, estimating the amount of materials for each archetype together with experts, and applying this information to an entire geographical area, such as a city or a country [46–48]. Because buildings contain a large amount of materials, and because of the availability of cadastre data, urban mining studies often focus on construction materials.

The increased understanding in urban mining has inspired various concepts that resemble circular hubs, in the form of pilot projects and proposals in gray literature. Examples are urban resource centers, which are smaller scale and closer to citizens [49], building material banks, which collect, store, and re-sell building materials [8], or building logistics hubs, in which building materials are collected in one facility and redistributed to multiple construction sites in order to improve transportation efficiency [50].

From literature on industrial clusters and urban mining, the concept of "circular construction hubs" can be understood in two ways: as industrial hubs or clusters, where circular companies are close to one another in order to share and exchange resources and knowledge, or as urban mining hubs, where materials are collected, stored, processed, and re-distributed.

Building on these two perspectives, a limited number of spatial data analysis studies have emerged, identifying the potential locations of circular hubs. Studies have identified clusters of circular industrial activity at both the national and European scale, and efforts have also been made to identify potential locations of urban mining facilities [11, 38, 51, 52].

In addition to academic literature, there has also been interest in circular hubs in Dutch governmental policy. This can be seen in both governmental strategy documents on CE and spatial development, which often envision circular hubs for the construction sector. Circular hubs have been mentioned in governmental strategic documents at both the provincial [22, 23, 53] and municipal level [24–26].

The recent interest in circular hubs stems from the risks and limitations associated with centralized global supply chains, which were further heightened by the COVID-19 pandemic and mutating geopolitical relationships [54, 55]. Manufacturing companies are rethinking their import and export strategies [56], making it more likely that European and Dutch policies will value local sourcing and production using secondary materials.

Currently, literature taking a spatially explicit view on circular hubs, or identifying spatial parameters for locating circular hubs, is limited. From the industry or industrial symbiosis perspective, much more attention is placed on technical solutions, such as possible material or energy exchanges between industrial facilities, or business management perspectives, such as how issues of ownership, company retention, and network typologies affect the environmental performance of industrial clusters. Although there have been studies explaining how transportation distance is limited to material value, weight, or company diversity, these studies ignore other location factors such as accessibility, labor availability, plot size, and land use constraints.

Additionally, existing spatially explicit CE studies are not identifying future potential locations of circular hubs. Instead, they are mapping existing phenomena—circular clusters [11, 38] and material stock [47]. Spatially explicit studies from the industrial perspective identify existing industrial clusters for CE, but do not speculate where these clusters will be in the future. Most spatial studies from the urban mining perspective focus on the location and availability of existing material stock, without identifying potential future locations of circular hubs.

There are three research aims for this study. The first aim is to categorize the different types of circular hubs for the construction industry, both from industrial and urban mining perspectives. The second is to collect spatial parameters required for finding suitable locations for each type of circular hub. The parameters should combine both the industrial symbiosis and urban mining perspectives, incorporating other spatial factors such as proximity to other companies, labor availability, or land use. The third is to translate the spatial parameters into a list of data and spatial analysis methods that could be used to identify potential future locations of circular hubs.

For this study, circular construction hubs are defined as locations that are attractive for circular companies in the construction sector. These companies are part of the waste to resource supply chain. They can be building material banks, building logistics hubs, or manufacturers of building products that use waste as raw material. Circular construction hubs can vary in a variety of ways. They can vary in spatial scale, operating within neighborhoods, cities, provinces, or even countries. They can vary in terms of target groups, working with citizens, start-ups, established companies, or governmental organizations. They can vary in terms of ownership, and can be owned by port authorities, industrial estates, governments, or not-for-profit foundations.

The main research question of this study is therefore, "What are the spatial parameters for locating circular construction hubs in the Netherlands?", which will be answered by the sub-research questions: "How can circular construction hubs in the Netherlands be spatially categorized, and what are the different types?" and "What are the spatial data and analysis methods required to identify the potential locations of circular construction hubs in the Netherlands?".

To summarize, there are three main motivations behind this study, which are addressed by the research questions above. Firstly, within the field of circular cities, there is an increasing interest in developing the concept of circular hubs, both by policy makers and academics. However, the current concept is not well defined yet, and has a variety of different perspectives. This issue is addressed by the first sub-research question, "How can circular construction hubs in the Netherlands be spatially categorized, and what are the different types?".

Secondly, there is a limited understanding of space in circular cities literature, even though academics have already been advocating for the importance of space (or geography) for a circular economy. This study provides a spatial perspective to circular cities literature, specifically to circular hubs, by answering the main research question, "What are the spatial parameters for locating circular construction hubs in the Netherlands?".

Finally, within the limited existing studies on circular economy, there are almost no studies exploring future spatial perspectives, speculating on future locations of circular infrastructure (such as circular hubs). This study therefore provides a future spatial perspective using the Netherlands as a case study, answering the sub-research question, "What are the spatial data and analysis methods required to identify the potential locations of circular construction hubs in the Netherlands?".

Methodology

The research question "What are the spatial parameters for circular construction hubs in the Netherlands?" was answered using the case study approach, gathering information from two sources: Dutch governmental policy documents on CE and spatial development and interviews with companies operating circular hubs. Spatial parameters for circular hubs were collected from four spatial perspectives: resources, accessibility, land use, and socio-economic.

The Netherlands as a Case Study

The Netherlands was used as a case study to understand the spatial parameters of circular construction hubs. The case study method was chosen because the topic of circular hubs is still a relatively new concept, making it more suited for exploratory research [57]. With a limited documentation of circular hubs in both academic and gray literature, more systematic research methods such as statistical analysis or literature review are not feasible. The case study approach is a well-established method that has been used in other academic studies related to circular cities—understanding patterns of circular transition in Belgian ports [58], city-level circular transitions in the Netherlands [59], and circular city types in Europe [13].

The Netherlands was chosen as the case study, because ideas related to circular economy are relatively well developed in the country, and are embedded in governmental policy at the national, provincial, and municipal level [10, 21, 26]. The Netherlands has had a circular economy strategy since 2017 [60], and circular economy concepts are integrated into the spatial development plans at the municipal and provincial scale [28, 29]. Moreover, the Netherlands also has an active circular building industry, partially encouraged by the government's emphasis on developing a circular economy. Organizations have started operating circular hubs—collecting, storing, processing, and redistributing various types of building materials, elements, and products. Using the Netherlands as a case study therefore allows for a multi-scalar understanding of the spatial parameters of circular hubs, from the perspectives of both policy and industry.

Document Review

The document review was conducted on Dutch governmental strategy documents on circular economy and spatial development. The aim of the review was to understand the aims of the Dutch government when it comes to circular construction hubs, as well as understanding hubs within the larger context of circular economy and spatial development policy in the Netherlands.

The circular economy documents were examined to extract spatial parameters when circular hubs were mentioned, while the spatial development documents were examined on how they incorporated circular hubs or clusters in their strategy. The parameters collected could be concrete requirements such as "requires industrial land with environmental category 3 or above," but can also be more vague, such as "hubs should allow citizens to get involved in neighborhood renovation activities." These more vague requirements can then be translated into concrete spatial parameters such as “within 1 km of high density residential areas.”

The criteria for document selection was that they needed to be published or commissioned by the Dutch government, be about circular economy or spatial development strategy, and can be at multiple governance scales. The CE-related documents were either circular economy strategy documents [26] or more in-depth research documents such as [61]. The spatial development strategy documents were documents produced at the municipal, provincial, and national scale, and were named “omgevingsvisie” in Dutch.

The documents were found using desk research, combining the search terms “circular economy” or “circulaire economie” and “omgevingsvisie” (spatial vision), together with the names of all provinces and major municipalities in the Netherlands. All provinces and major municipalities in the Netherlands had circular economy strategy documents, but some spatial development documents were omitted because they did not integrate a circular economy strategy.

In total, 24 documents were reviewed. Seventeen were on circular economy strategy, and 7 were spatial development documents. Table 1 below shows an overview of the documents.

Table 1 Overview of documents reviewed

Name	Scale	Strategy type
Chemport Europe—circular plastics northern Netherlands	1—area	Circular economy
Circular city port workbook—exploring the port region	1—area	Circular economy
M4H spatial framework	1—area	Spatial development
Amsterdam circular 2020–2025 strategy	2—city	Circular economy
Circular Amsterdam report	2—city	Circular economy
Circular Den Haag	2—city	Circular economy
Circular Rotterdam report	2—city	Circular economy
Omgevingsvisie Amsterdam (spatial vision Amsterdam)	2—city	Spatial development
The circular economy in Groningen, the Netherlands	2—city	Circular economy
Bouw Campus—circular resources center final report	3—region	Circular economy
Bouw Campus—towards a spatial and economic model for a circular resources cluster in Zuid Holland	3—region	Circular economy
Circular biz (circular business parks research in Zuid Holland)	3—region	Circular economy
Circular Gelderland	3—region	Circular economy
Circular Noord Nederland (northern NL provinces)	3—region	Circular economy
Circular North Holland	3—region	Circular economy
Circular Utrecht policy vision	3—region	Circular economy
Circular Zuid-Holland	3—region	Circular economy
Omgevingsvisie Provincie Noord Holland	3—region	Spatial development
Omgevingsvisie Provincie Utrecht	3—region	Spatial development
Omgevingsvisie Provincie Zuid Holland	3—region	Spatial development
Regions of the future	3—region	Spatial development
TNO—opportunities for circular bouwhubs in South Holland	3—region	Circular economy
National implementation agenda—Circular economy 2021–2023	4—country	Circular economy
National strategy on spatial planning and the environment	4—country	Spatial development

Semi-structured Interviews

The semi-structured interviews were conducted with circular construction companies that participate in the storage, redistribution, or processing of construction and demolition waste. The aim of the interviews was to understand how the construction industry viewed and implemented circular hubs, as well as gathering concrete spatial parameters such as facility sizes in square meters or travel distance limits in kilometers. The interviewees also provided more explanation about the spatial parameters, such as why a certain amount of storage space is needed, or why it is important to be located near a certain type of industry.

Most companies interviewed were based in the Netherlands, although there was one company from Belgium and another from Austria. The criteria for choosing the interviewees were that they worked in a company that participates in the collection, storage, redistribution, reselling, or processing of construction and demolition waste and had a good understanding of the company's operations. The companies chosen were required to be located in the Netherlands, or at least in a country nearby. The interviewees were found through email, a public post on LinkedIn, and personal contacts of colleagues in the Faculty of Architecture and the Built Environment at the Delft University of Technology.

The interview questions covered the companies' operations from the four spatial perspectives: resources, accessibility, land, and socio-economic. For the full list of questions, please refer to the supplementary document (online resource 2). Because these were semi-structured interviews, the amount of time spent on each question varied per interviewee, according to their expertise and interest. Table 2 below shows the list of interviewees. The interview transcripts can be found in the supplementary document (online resource 3).

Four Spatial Perspectives for Circular Hubs

The spatial parameters of circular construction hubs were collected from four spatial perspectives: resources, accessibility, land, and socio-economic. The collected parameters could then serve as an input for future studies using quantitative spatial analysis methods to identify locations of circular construction hubs.

Table 2 List of interviewees

Date	Name	Role	Company	Duration
30 May	Interviewee A	Commercial Manager for Circular & Renewable Industry	Port of Amsterdam	1 h
3 June	Interviewee B	Chief Marketing Officer	DHK Kozijnen	1 h
10 June	Interviewee C	Architect and civil engineer	BauKarussell	1 h
10 June	Interviewee D	Founder	Material Bank Leuven	45 min
17 June	Interviewee E	Program manager	TKI Dinalog	1 h
21 June	Interviewee F	Circularity and sustainability officer	Vlasman	1 h
21 June	Interviewee G	Circular Economy Advisor	KplusV	1 h
21 June	Interviewee H	Project manager	Fiction factory	1 h
24 June	Interviewee I	Founder	Stichting Insert	1 h
7 July	Interviewee J	Director	Buurman	1 h
15 July	Interviewee K	Circular Supply Specialist	New Horizon	1 h

"Resources" refers to the topic of location science in operations research, which uses optimization algorithms to determine where facilities should be located in order to minimize the cost of satisfying demands [62]. Relevant spatial parameters from this perspective are the types of suppliers and clients (such as material and building types) for circular construction hubs, as well as travel distance limits.

"Accessibility" refers to transportation network analysis, which uses network analysis methods to understand the accessibility of locations on a transportation network, such as streets or waterways [63]. Relevant spatial parameters from this perspective are the scale of accessibility for different types of circular hubs and their mode of transportation.

"Land" refers to urban morphology research, which provides a quantitative understanding of the morphology of buildings, plots, and urban blocks [64, 65]. Relevant spatial parameters from this perspective are building size and height, plot size, street frontage, plot diversity, and land use restrictions.

"Socio-economic" refers to economic geography research, which studies the spatial factors affecting location of companies, such as labor availability, agglomeration of companies, and local taxation policy. For this study, relevant parameters are labor availability and proximity to other companies [66, 67].

As mentioned in the beginning of this section, the spatial parameters were collected with two methods: document review and semi-structured interviews.

Results

From the interviews and document reviews, four types of circular construction hubs were identified: craft centers, industry hubs, local material banks, and urban mining hubs. These hub types were categorized by their spatial scale of operations (regional versus local), and whether they had a focus on processing or redistributing secondary materials (industry versus logistics perspective). The four categories can be seen in Fig. 1 below.

Circular industry hubs house large-scale and industrial circular activity, and process bulk construction materials such as asphalt and concrete. They operate at a large scale, at a provincial or even national level, and can benefit from water transport. They require high environmental category land and large plot sizes. They could benefit from co-locating with existing industrial or recycling clusters.

Urban mining hubs are for sorting, storing, and distributing building components and products (whereas bulk building materials are processed in industrial hubs). They can work as a "hub-and-spoke" system, with a larger scale central hub connected to a network of smaller scale "satellite hubs." The smaller satellite hubs are 5–10 ha, with an environmental category of 2–3.

Circular craft centers use residue construction flows to make smaller scale products, such as furniture or retail spaces. Suppliers and customers are usually located within the same city, connected using the road network. It is often connected to a local material bank, which is a large space that stores materials. Often, local labor is used, and there is also usually a "citizen-facing" component to the operations of a craft center—locals either attend workshops or supply or buy materials from the center.

Local material banks collect, store, and re-sell residue flows ignored by larger companies, and are usually co-located with craft centers (or owned by the same organization). Materials are usually collected and sold within the same city, using road transportation. A

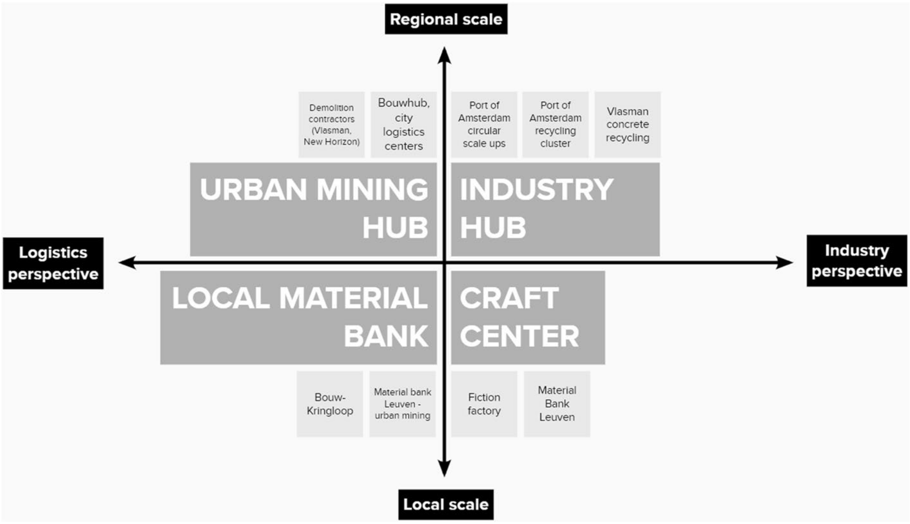

Fig. 1 Diagram showing the four types of circular construction hubs: urban mining hub, local material hub, industry hub, and craft center

large space with high ceilings (1200–1500 m^2) is required for storage of materials. People with a distance from the labor market are often employed for operations.

Table 3 summarizes the spatial parameters for the four hub types from four perspectives—resources, accessibility, land, and socio-economic. Spatial parameters, data, and analysis methods are further explained and elaborated in the "Discussion" section, and full details are listed in the supplementary excel sheet (online resource 1).

Spatial Parameters, Data, and Analysis Methods for Each Circular Hub Type

The spatial parameters, data, and analysis methods for each circular hub type are summarized in the paragraphs below. The spatial parameters are categorized into four perspectives: resources, accessibility, land, and socio-economic. For more details, please refer to the "Methodology" section. For more details on spatial parameters, such as environmental categories or waterway sailing classes, please refer to the supplementary excel sheet (online resource 1).

The spatial analysis methods recommended in this section are site selection, spatial clustering, and facility location. Site selection analysis selects the best location or site for a facility based on spatial criteria such as proximity to amenities, availability of materials, or accessibility [68, 69]. Spatial clustering analyzes the degree of clustering of points distributed in space, and allows for the identification of hotspots [11, 70]. Facility location analysis identifies the optimal placement of facilities to minimize transportation costs [71].

Industry Hubs

For "resources" parameters, industry hubs process bulk construction materials such as asphalt, concrete, sand, gravel (Interviewee F) [61], and top-soil (Interviewee C). These

Table 3 Summary of spatial parameters for four types of circular construction hubs. For the full list, please refer to the supplementary excel sheet (online resource 1)

	Resource perspective	Accessibility perspective	Land use perspective	Socio-economic perspective
Craft center	Works with materials with smaller scales, sometimes with a shorter life cycle, such as wood for furniture workshops Both the suppliers and customers are citizens, and citizen workshops are hosted, so are close to urban areas	Suppliers and customers are located within the same city (10–20 km) Road is the main type of transportation, Water transportation does not make sense because flows are not large/consistent enough	Buildings of 1200–1500 m^2 with loading and unloading areas needed Exemptions are often made for craft centers. They do not fit into industrial land because they have social activities like workshops, and they do not fit into cultural land because they have industrial machinery	craft centers should be close to human capital (mix of skills—designers, craftsmen, people with distance from labor market), as well as citizens for educational purposes
Industry hub	Processing bulk construction materials such as asphalt, concrete, soil, sand, and gravel They can be part of a recycling cluster, mainly focused on recycling as it is currently most profitable	The suggested scale varies from 1 hub per province to 1 hub for the whole of western Europe. The transportation limit for asphalt and concrete is 50-100 km Currently, road transport is used, but there is interest in using waterways of class III or higher, as bulk transportation is cheaper and more sustainable on water	10–30 ha, usually located in existing ports or (industrial) business parks, environmental category 4.1 or higher	Can build on existing recycling capacity, embedded in ecosystem of circular industry and construction companies
Local material bank	materials for small scale private housing renovations, governmental or university buildings, or furniture Targets smaller residue flows that larger companies ignore	materials are collected and sold within the same city, 10–20 km Typically road transportation is used. Water transportation is interesting for scaling up	1200–1500 m^2. Large amount of storage space is needed because building materials are bulky. Existing buildings with loading areas and high ceilings are preferred	Work with people with a distance from the labor market, and be near other hardware stores or thrift stores

Table 3 (continued)

	Resource perspective	Accessibility perspective	Land use perspective	Socio-economic perspective
Urban mining hub	Urban mining hubs redistribute building elements (e.g., bricks) or products (e.g., doors) from housing, governmental buildings, and offices There is potential to combining logistics hubs with circular hubs to reduce transportation emissions and encourage a more "demand-driven" hub	Currently, service areas vary from 30–50 km. One way to determine the scale would be to optimize environmental impact and supply–demand matching Road transport is used, although there is interest in connecting to water and rail networks at larger scales	Plot sizes are 5–10 ha, with environmental category of 2 or above Temporary storage could be vacant plots and demolition sites, and more fixed hubs could use existing ports, industrial estates or business parks	Hubs could be made by expanding existing clusters of concrete plants, waste processors, or construction hubs While some say that combining logistics with industry could be useful, others claim that there is no benefit (or problem) with combining bulk material processing and building product (reverse) logistics Some hubs work with people with a distance from the labor market

processing methods are different from processing building products such as windows, so there is no clear benefit to placing them together on the same site [72].

For accessibility parameters, the suggested scale for industry hubs varies—some sources suggest there is potential to expand to the whole of western Europe (Interviewee A), while others suggest there should be 1 hub per province, connected with a number of construction hubs at a local level, suggesting a “hub-and-spoke” system operating at multiple scales [61]. However, the transportation distance limit for asphalt and concrete is around 50–100 km (Interviewee K) [61]. While the road network is currently used (Interviewee F), there is interest in using waterways (Interviewee A) [27, 39] of class III or higher [61] for transportation, as it is cheaper and more sustainable to transport bulk materials on water.

For land use parameters, industry hubs are usually located in existing ports or industrial parks, preferably with a hard boundary from residential areas to give greater long-term location and investment security [28]. Larger plots of 10–30 ha are needed [61], and should have an environmental category of 4.1 or higher to avoid nuisance [28, 61, 72]. Additionally, major landfalls for offshore renewable energy could be attractive for circular companies that want to combine circular economy and energy ambitions. These landfalls are ports and industrial areas near the coast of the Netherlands [27].

For socio-economic parameters, a strong local ecosystem is needed, consisting of innovative circular industry and supply chains (Interviewee A), construction-related companies [21, 26], and existing recycling capacity (Interviewee A) [61], in order to form circular clusters [21, 22] and share energy, space, materials, and knowledge (Interviewee A) [21, 22, 26].

To identify suitable plots for industry hubs, the following spatial analysis steps can be taken. For data required for each step, please refer to the supplementary excel sheet (online resource 1). Find industrial estates with an environmental category of 4.1–4.2, with plots of at least 10–30 ha. Then, find hotspots of bulk construction waste recyclers with spatial clustering methods such as local Moran’s I [11] or DBSCAN [38]. Rank industrial estates by their distance away from nearest residential areas (the further the better), whether there is hard boundary between the plot and nearby residential areas, as well as proximity to major landfalls of offshore renewable energy and recycling clusters.

To take into account the material yield for industry hubs, the following steps can be taken: From the chosen industrial estates, find locations that can reach a high supply and demand of bulk materials within a 50-km travel distance limit on the road network, and prioritize locations that are next to waterways. The location and availability of bulk materials (concrete, asphalt, sand, top-soil) can be identified using in two ways: firstly, future supply of concrete, sand, and asphalt can be found in data on future demolition sites, in which the availability of the bulk materials is estimated. Secondly, the future supply of top-soil can be found in data on future construction sites that overlap with greenfields.

Urban Mining Hubs

For resources parameters, urban mining hubs deal with building materials and products that do not need processing before redistribution [72]. This can include building elements (e.g., bricks) or products (e.g., doors) (Interviewee F, K), greenery (Interviewee C, I), and infrastructure elements. Housing, governmental buildings, and offices can be prioritized. Housing and offices are attractive because they often have standardized materials, and require regular renovations (Interviewee I, K). Government buildings are backed by the governmental circular public procurement strategies, which allow for more centralized coordination of construction and demolition [53, 73].

For accessibility parameters, interviewed hubs state that they are currently serving clients within their own city, meaning the operations scale is around 30–50 km (Interviewee A, C, F, I). The road network is usually used because it is more efficient and reliable than waterways (Interviewee B, F, I) [72]. There is interest in using waterways or railways to reduce environmental impact, but flows are not large enough to make this financially feasible (Interviewee A, C, K) [39].

For land use parameters, existing ports, industrial estates, or business parks can be used [22, 24, 73], with plots that range from 1 to 10 ha, with an environmental category of at least 2 (Interviewee I) [39, 72]. Large plots are required because building materials are bulky, fragile, and difficult to stack (Interviewee B, C).

For socio-economic parameters, urban mining hubs could be made by expanding existing construction logistics hubs [72], and should be close to possible customers, such as building product resellers and construction companies. Manual labor is required; some hubs work with people with a distance from the labor market (Interviewee C, F, I).

To identify suitable plots for urban mining hubs, the following spatial analysis steps can be taken. For data required for each step, please refer to the supplementary excel sheet (online resource 1). Select existing industrial estates with plots of at least 5 ha, with environmental category of 2–3, near populations of low income and low education (as some hubs work with people with a distance from the labor market). Then, identify hotspots for waste processors and building product resellers using local Moran's I [11] or DBSCAN [38], and rank the selected locations by their distance from hotspots.

To take into account the material yield for urban mining hubs, the following steps can be taken: From the chosen industrial estates identified in the previous steps, find locations that can reach a high supply and demand of materials suitable for urban mining hubs within a 50-km radius—these are building elements from housing, governmental buildings, and offices, with a priority for large buildings, as they are more attractive to demolition companies. Additionally, locations of high yield can also be ranked by their multi-modal accessibility. This can be understood by seeing if the location can access multiple modes of transport—road, water, and rail.

Craft Hubs

Through the interviews, we found that local material banks and craft centers are often two departments run by the same organization, in the same locations, with very similar spatial requirements (Interviewee D, J). These two types were therefore combined into one—craft hubs.

For resources parameters, craft hubs collect residue waste from the building industry that larger companies ignore, often wood from public buildings. Its customers are private individuals, who use these materials for small-scale projects like renovations and furniture (Interviewee D, J).

For accessibility parameters, materials are collected and sold within the same city, although some customers are willing to travel further for a cheaper product. Roads are the main mode of transportation, although there is interest in waterways when operations scale up (Interviewee D, G, J).

For land use parameters, around 1–2 ha is needed, as a large amount of storage space is needed for bulky building materials. Existing and often abandoned buildings with good loading areas are used to save costs (Interviewee D, J).

For socio-economic parameters, craft hubs are closer to residential areas because they hold workshops, sell to citizens, and work with people with a distance from the labor market. They can also be close to hardware stores or thrift stores, as they share similar customers (Interviewee D, G, J).

To identify suitable plots for craft hubs, the following spatial analysis steps can be taken. For data required for each step, please refer to the supplementary excel sheet (online resource 1). Filter locations within 1 km (15-min walk) from housing or commercial areas, prioritizing locations near high population density and high diversity of population income and education level, as well as accessible by public transport and bicycle network. Then, find buildings of at least 1200 m^2 in size. Prioritize older buildings, as they will more likely be abandoned. Then, find hotspots of hardware stores and thrift shops with local Moran's I [11] or DBSCAN [38], and rank locations according to distance from hotspots.

To take into account the material yield for craft hubs, the following steps can be taken: Taking the chosen locations from the previous steps, find locations that can reach a high supply and demand for wood from housing and governmental buildings within a 30-km travel distance limit. Locations of material supply is defined by future demolition site locations, and demand is estimated by population location. Population numbers (instead of future construction sites) should be used to estimate demand, because most craft hub consumers are using the materials for consumer products, such as wooden furniture.

From Site Suitability to Facility Location

The spatial analysis methods listed above create suitability maps—maps that show the locations that could be potentially attractive to circular hubs, without specifying how many of these locations would actually be used in a fully functioning circular building economy. The suitability maps can therefore be further elaborated into facility location maps, which use facility location algorithms to identify the number and locations of hubs that would hypothetically be required if all available building materials were to be processed by circular construction hubs [62]. The potential and number of facilities are identified by minimizing the travel distance from the facility (the circular hub) to its suppliers (demolitions sites) and customers (construction sites).

Discussion

From the interviews, we found that the concept of circular construction hubs is a contested issue. While many policy documents assume that there is a need for a centralized "hub" for storing, processing, and redistributing secondary construction resources, not all interviewees saw the necessity in this. Some demolition contractors do not need a "hub" to operate (Interviewee C, F, K). Instead, materials are immediately collected from the demolition site and sold to nearby construction material recyclers and dealers. However, hubs are still necessary because a longer term storage location makes it more likely that materials will be reused instead of recycled. More importantly, even if demolition contractors do not need a hub, a storage location is still needed by construction material dealers and recyclers, who could also be located on circular hubs.

Three Perspectives for Circular Construction Hubs

The concept of circular construction hubs seems to have emerged from three perspectives—urban mining, logistics, and craft. The urban mining perspective argues that hubs are necessary because it is impossible to match supply and demand of secondary construction resources within a narrow timeframe. Resources supplied from demolition sites today might not be needed until next year. A "hub" is needed to store resources for a longer time to increase the chances of reuse. This perspective is mainly taken by demolition companies and their partners in their network.

The logistics perspective argues that existing construction logistics hubs, where primary materials are efficiently organized and then distributed to construction sites, can re-distribute secondary materials as well. This perspective is mainly taken up by construction companies and researchers in construction logistics.

The craft perspective argues that citizens and small companies should get involved in the circular economy and that circular making activities should be reintroduced into cities via neighborhood hubs or maker spaces. This perspective is taken by community-based organizations.

Alternative Models for Circular hubs

The spatial parameters listed in the "Results" section (Table 3) focus on the operations of a single hub on a permanent location. However, three other network models have been proposed by interviewees to identify the locations of circular hubs—decentralized (and temporary) hub network, multi-scale hub-and-spoke network, and spatially optimized hubs.

The concept of a decentralized hub network comes from interviewed demolition contractors. Instead of working with a centralized "hub," materials are stored directly on the demolition site or nearby vacant land, and then by nearby building material resellers (Interviewee C, F, K). This avoids unnecessary transportation and storage costs, and takes advantage of existing storage capacity of partners. The resulting hubs could be smaller, temporary, and decentralized, leading to hub locations that change over time, according to the changing locations of temporary vacant land and demolition sites.

The hub-and-spoke network would consist of a "central" hub surrounded by a network of "satellite" hubs [72]. A potential spatial analysis method would be to first identify the "satellite" hubs with facility location analysis, in order to minimize the travel distance between each satellite hub and individual demolition and construction sites. Then, the same method can be used to determine central hub locations, minimizing the travel distance between each central hub and nearby satellite hubs (instead of individual demolition or construction sites). Additionally, hub location methods, an important sub-field of location science, could be used to identify the location of interacting hub facilities [74].

While most interviewees have provided an approximate service area of their hub (e.g., "our partners are generally within a 30 km radius from us"), some interviewees have suggested spatial optimization as a way of determining the scale and locations of hubs. The larger the service area of a hub, the more likely supply of building materials can be matched with demand. However, larger service areas also increase transportation emissions. There is therefore an opportunity to use spatial optimization methods [75] to balance between these two opposing factors to find a suitable service area of a circular hub (Interviewee E, K) [52].

Conclusion

In conclusion, this paper provided a spatially explicit perspective to the study of the circular built environment by answering the research question, "What are the spatial parameters for circular construction hubs in the Netherlands?" The research question was answered through a document review of Dutch governmental policy documents and interviews with circular construction companies involved in the collection, storage, processing, and redistribution of construction and demolition waste.

This study categorized circular construction hubs into four types: urban mining hubs, industry hubs, craft centers, and local material banks. For each type of hub, spatial parameters were collected from four perspectives: resources (material and building types, business model), accessibility (mode and scale of transportation), land use (land use, plot size), and socio-economic (proximity to other companies, labor). The spatial parameters were then translated into spatial data and analysis methods that could be used to find potential locations for each type of circular construction hub. The most promising spatial analysis methods were site selection analysis, facility location analysis, and spatial optimization between travel distance emissions costs and embodied emissions savings from secondary resource use.

This study provides both theoretical and practical contributions to existing knowledge and practice on the circular built environment. In terms of theoretical contributions, this study provides an overview of different types of circular construction hubs in the context of the Netherlands. By focusing on spatial parameters, this study contributes to developing a spatially explicit understanding of the circular built environment. This was done by combining spatial perspectives from different disciplines: location theory, economic geography, and urban morphology.

The spatial parameters, data, and analysis methods identified can be directly implemented into a quantitative analysis study to identify future locations of circular construction hubs. We believe this type of study would be most useful if conducted at the provincial or national scale in the Netherlands. It could help policy makers prioritize existing industrial estates for implementing the circular economy.

Limitations

While this study provides spatial parameters for circular hubs, the locations of hubs do not only depend on geographical factors like proximity or accessibility, but also on social factors like existing company networks. Hubs could choose their location based on personal connections with local stakeholders, such as existing companies or industrial estate managers. These factors are not captured by the spatial perspectives chosen for this study.

While the suggested spatial analysis methods provide a first step to identifying the location of circular construction hubs in a quantitative manner, more understanding on the exchange and storage of secondary building resources is required in order to increase the accuracy of these methods. Currently, there are no detailed studies on how different material types have different transportation limits, how to calculate the yield of different building types in terms of building elements or products instead of materials, the amount of time different building elements and products are stored in a circular economy, and the relationship between material storage time and the amount of space required.

Finally, this study was a single case study on the Netherlands, which is not as rigorous of a multiple case study comparing the parameters for different countries. Because of this, results generated for this study are only applicable to the Netherlands (and perhaps nearby countries), but not to other contexts. For example, the almost unanimous interest in water transport is only relevant to countries with a functioning water transport infrastructure.

Recommendations for Further Research

The spatial parameters identified in this study can be used to identify locations of circular hubs in the Netherlands using spatial analysis methods such as multi-criteria site selection, spatial agent based modeling, spatial optimization, and hub location. The result can be maps of the Netherlands that show potential locations for different types of circular hubs, which could be useful to spatial policy makers in the Netherlands.

The locations of circular hubs can be further studied from a social, economical, or political perspective, in order to understand the factors that attract companies to a certain location, in addition to geographical factors.

A dataset could be developed to identify the amount of building products and elements in different building types. While urban mining datasets already estimate the amount of materials per building type, the next step is to create an ontology that connects building types to building products and elements. Having an inventory on the location and availability of building products and elements will allow for a more detailed distinction between industry hubs, which process bulk materials, and urban mining hubs, which process building elements and products.

More could also be understood on the relationship between distance, time, and the movement of building materials. Studies could explore how different attributes of building (secondary) resources, such as value, weight, or volume, could affect the amount of time it gets stored in a hub, or the distance stakeholders are willing to travel to exchange it.

Finally, this study's methods can be applied to other countries in order to identify the spatial parameters of circular hubs in different cultural and geographical contexts.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43615-023-00285-y.

Acknowledgements The authors would like to sincerely thank the interviewees for their time and important insights.

Funding This research received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 821479.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Krausmann F et al (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc Natl Acad Sci 114(8):1880–1885. https://doi.org/10.1073/pnas.1613773114
2. Schandl H, Fischer-Kowalski M, West J et al (2016) Global material flows and resource productivity - Summary for policy makers. United Nations Environment Programme, Paris
3. Levermore G (2008) A review of the IPCC Assessment Report Four, Part 1: the IPCC process and greenhouse gas emission trends from buildings worldwide. Build Serv Eng Res Technol 29(4):349–361. https://doi.org/10.1177/0143624408096263
4. Urge-Vorsatz D, Lucon O, Akbari H et al (2014) Chapter 9: Buildings. In: Working Group III contribution to the IPCC 5th Assessment Report "Climate Change 2014: Mitigation of Climate Change." Cambridge University Press, Cambridge, UK
5. Fishman T, Schandl H, Tanikawa H (2016) Stochastic analysis and forecasts of the patterns of speed, acceleration, and levels of material stock accumulation in society. Environ Sci Technol 50(7):3729–3737. https://doi.org/10.1021/acs.est.5b05790
6. Commission E (2020) A new Circular Economy Action Plan. Belgium, Brussels
7. Kirchherr J, Reike D, Hekkert M (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232. https://doi.org/10.1016/j.resconrec.2017.09.005
8. Marin J, Alaerts L, Van Acker K (2020) A materials bank for circular leuven: how to monitor 'messy' circular city transition projects. Sustainability 12(24):10351. https://doi.org/10.3390/su122410351
9. Ness DA, Xing K (2017) Toward a resource-efficient built environment: a literature review and conceptual model: towards a resource efficient built environment. J Ind Ecol 21(3):572–592. https://doi.org/10.1111/jiec.12586
10. Het ministerie van Infrastructuur en Waterstaat (2021) Uitvoeringsprogramma Circulaire Economie 2021-2023. Rijksoverheid, Den Haag
11. Tsui T, Derumigny A, Peck D et al (2022) Spatial clustering of waste reuse in a circular economy: a spatial autocorrelation analysis on locations of waste reuse in the Netherlands using global and local Moran's I. Front Built Environ 8. https://doi.org/10.3389/fbuil.2022.954642
12. Williams J (2019) Circular Cities: Challenges to Implementing Looping Actions. Sustainability 11(2):423. https://doi.org/10.3390/su11020423
13. Prendeville S, Cherim E, Bocken N (2018) Circular cities: mapping six cities in transition. Environ Innov Soc Transit 26:171–194. https://doi.org/10.1016/j.eist.2017.03.002
14. Amenta L et al (2019) Managing the transition towards circular metabolism: living labs as a co-creation approach. Urban Plan 4(3):5–18. https://doi.org/10.17645/up.v4i3.2170
15. Dijst M et al (2018) Exploring urban metabolism—towards an interdisciplinary perspective. Resour Conserv Recycl 132:190–203. https://doi.org/10.1016/j.resconrec.2017.09.014
16. Broto VC, Allen A, Rapoport E (2012) Interdisciplinary perspectives on urban metabolism. J Ind Ecol 16(6):851–861. https://doi.org/10.1111/j.1530-9290.2012.00556.x
17. Kennedy C, Cuddihy J, Engel-Yan J (2007) The changing metabolism of cities. J Ind Ecol 11(2):43–59. https://doi.org/10.1162/jie.2007.1107
18. Bahers JB, Athanassiadis A, Perrotti D, Kampelmann S (2022) The place of space in urban metabolism research: towards a spatial turn? A review and future agenda. Landsc Urban Plan 221:104376. https://doi.org/10.1016/j.landurbplan.2022.104376
19. Tapia C, Bianchi M, Pallaske G, Bassi AM (2021) Towards a territorial definition of a circular economy: exploring the role of territorial factors in closed-loop systems. Eur Plan Stud 29(8):1438–1457. https://doi.org/10.1080/09654313.2020.1867511
20. Furlan C, Wandl A, Cavalieri C, Unceta PM (2022) Territorialising circularity. In: Amenta L, Russo M, van Timmeren A (eds) Regenerative Territories: Dimensions of Circularity for Healthy Metabolisms. Springer International Publishing, Cham, pp 31–49. https://doi.org/10.1007/978-3-030-78536-9_2
21. Provincie Zuid Holland (2019) Circulair Zuid-Holland - samen versnellen. In: Provincie Zuid Holland. https://circulair.zuid-holland.nl/activiteit/3020/#:~:text=De%20strategie%20'Circulair%20Zuid%2DHolland,Nederlandse%20economie%20circulair%20te%20maken.&text=Circulair%20Zuid%2DHolland.,vastgesteld%20door%20de%20Provinciale%20Staten. Accessed 1 Sep 2022
22. Noord-Holland (2021) Actieagenda Circulaire Economie 2021-2025 - Provincie Noord-Holland. https://www.noord-holland.nl/Onderwerpen/Klimaat_Energie/Circulaire_economie/Documenten/Actieagenda_Circulaire_Economie_2021_2025. Accessed 29 Jun 2023
23. Metabolic (2018) Noord-Nederland Circulair. https://www.metabolic.nl/publications/noord-nederland-circulair/. Accessed 29 Jun 2023

24. Metabolic, Circle Economy, Blue City, and Spring Associates (2018) Circular Rotterdam: new jobs in a zero waste economy. Metabolic. https://www.metabolic.nl/projects/circular-rotterdam/. Accessed 29 Jun 2023
25. Gemeente Den Haag (2018) Circulair Den Haag - Transitie naar een duurzame economie. https://denhaag.raadsinformatie.nl/modules/13/Overige%20bestuurlijke%20stukken/440072. Accessed 29 Jun 2023
26. Gemeente Amsterdam (2020) Amsterdam Circulair 2020 - 2025. In: Amsterdam.nl. https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/coalitieakkoord-uitvoeringsagenda/gezonde-duurzame-stad/amsterdam-circulair-2020-2025/. Accessed 29 Jun 2023
27. Ministry of the Interior and Kingdom Relations (2020) National strategy on spatial planning and the environment. Ontwerp NOVI. https://www.novistukken.nl/english/default.aspx. Accessed 29 Jun 2023
28. Zuid-Holland (2021) Omgevingsbeleid. Provincie Zuid-Holland. https://www.zuid-holland.nl/onderwerpen/omgevingsbeleid/. Accessed 29 Jun 2023
29. Gemeente Amsterdam (2021) Omgevingsvisie Amsterdam 2050. Amsterdam2050. https://amsterdam2050.nl/. Accessed 29 Jun 2023
30. Schiller F, Penn A, Druckman A, Basson L, Royston K (2014) Exploring space, exploiting opportunities: the case for analyzing space in industrial ecology. J Ind Ecol 18(6):792–798. https://doi.org/10.1111/jiec.12140
31. Bourdin S, Galliano D, Gonçalves A (2021) Circularities in territories: opportunities & challenges. Eur Plan Stud 30(7):1–9. https://doi.org/10.1080/09654313.2021.1973174
32. Chertow MR, Ashton WS, Espinosa JC (2008) Industrial symbiosis in Puerto Rico: environmentally related agglomeration economies. Reg Stud 42(10):1299–1312. https://doi.org/10.1080/00343400701874123
33. Desrochers P (2000) Market processes and the closing of 'industrial loops'.: a historical reappraisal. J Ind Ecol 4(1):29–43. https://doi.org/10.1162/108819800569276
34. Porter M (1998) Clusters and the new economics of competition. Harv Bus Rev 76:77–90
35. Harrison B, Kelley MR, Gant J (1996) Innovative firm behavior and local milieu: exploring the intersection of agglomeration, firm effects, and technological change. Econ Geogr 72(3):233. https://doi.org/10.2307/144400
36. Hoover E (1937) Location theory and the shoe leather industries, vol 55. Harvard University Press, Cambridge, MA
37. Jacobs J (1969) The economy of cities. Random House, New York
38. Mendez Alva F, De Boever R, Van Eetvelde G (2021) Hubs for circularity: geo-based industrial clustering towards urban symbiosis in Europe. Sustainability 13(24):13906. https://doi.org/10.3390/su132413906
39. Circular Flanders (2021) Third Workbook - Exploring the Port Region. Circular Flanders. https://circularports.vlaanderen-circulair.be/third-workbook-exploring-the-port-region/. Accessed 29 Jun 2023
40. Domenech T, Bleischwitz R, Doranova A, Panayotopoulos D, Roman L (2019) Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. Resour Conserv Recycl 141:76–98. https://doi.org/10.1016/j.resconrec.2018.09.016
41. Jensen PD, Basson L, Hellawell EE, Bailey MR, Leach M (2011) Quantifying 'geographic proximity': experiences from the United Kingdom's National Industrial Symbiosis Programme. Resour Conserv Recycl 55(7):703–712. https://doi.org/10.1016/j.resconrec.2011.02.003
42. Jensen PD (2016) The role of geospatial industrial diversity in the facilitation of regional industrial symbiosis. Resour Conserv Recycl 107:92–103. https://doi.org/10.1016/j.resconrec.2015.11.018
43. Lyons DI (2008) A Spatial analysis of loop closing among recycling, remanufacturing, and waste treatment firms in Texas. J Ind Ecol 11(1):43–54. https://doi.org/10.1162/jiec.2007.1029
44. Lyons D, Rice M, Wachal R (2009) Circuits of scrap: closed loop industrial ecosystems and the geography of US international recyclable material flows 1995–2005: Circuits of scrap: US international recyclable material flows 1995–2005. Geogr J 175(4):286–300. https://doi.org/10.1111/j.1475-4959.2009.00341.x
45. Sterr T, Ott T (2004) The industrial region as a promising unit for eco-industrial development—reflections, practical experience and establishment of innovative instruments to support industrial ecology. J Clean Prod 12(8–10):947–965. https://doi.org/10.1016/j.jclepro.2004.02.029
46. Tanikawa H, Fishman T, Okuoka K, Sugimoto K (2015) The weight of society over time and space: a comprehensive account of the construction material stock of Japan, 1945–2010: the construction material stock of Japan. J Ind Ecol 19(5):778–791. https://doi.org/10.1111/jiec.12284
47. Sprecher B, Verhagen TJ, Sauer ML, Baars M, Heintz J, Fishman T (2021) Material intensity database for the Dutch building stock: towards Big Data in material stock analysis. J Ind Ecol 26(1):272–280. https://doi.org/10.1111/jiec.13143

48. Verhagen TJ, Sauer ML, van der Voet E, Sprecher B (2021) Matching demolition and construction material flows, an urban mining case study. Sustainability 13(2):653. https://doi.org/10.3390/su13020653
49. Urban Agenda for the EU (2019) Futurium | Circular Economy - Urban Resource Centre. https://futurium.ec.europa.eu/en/urban-agenda/circular-economy/library/urban-resource-centre. Accessed 29 Jun 2023
50. TNO (2018) "Duurzame Bouwlogistiek voor Binnenstedelijke Woning- en Utiliteitsbouw - ervaringen en aanbevelingen"
51. Misra S et al (2019) Eds., p535 - Location Theory in CE - in Computational Science and Its Applications – ICCSA 2019: 19th International Conference, Saint Petersburg, Russia, July 1–4, 2019, Proceedings, Part III, vol. 11621. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-24302-9
52. Hodde J (2021) Scoping the circular economy - finding optimal spatial distribution of concrete recycling facilities. Dissertation, University of Wageningen
53. Provincie Gelderland (2022) CircE - European regions towards circular economy, Action Plan, Province of Gelderland. https://gelderland.stateninformatie.nl/document/8107246/1/CW_-_Bijlage_3_CircE-actieplan_(PS2019-749). Accessed 29 Jun 2023
54. Dumée LF (2022) Circular materials and circular design—review on challenges towards sustainable manufacturing and recycling. Circ Econ Sustain 2(1):9–23. https://doi.org/10.1007/s43615-021-00085-2
55. Wuyts W, Marin J, Brusselaers J, Vrancken K (2020) Circular economy as a COVID-19 cure? Resour Conserv Recycl 162:105016. https://doi.org/10.1016/j.resconrec.2020.105016
56. Vet JMD, Nigohosyan D, Ferrer JN et al (2021) Impacts of the COVID-19 pandemic on EU industries. https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2021)662903. Accessed 1 Sep 2022
57. RK Yin (2015) "Case studies" in *International Encyclopedia of the Social & Behavioral Sciences*, Elsevier, 194–201. https://doi.org/10.1016/B978-0-08-097086-8.10507-0
58. Haezendonck E, Van den Berghe K (2020) Patterns of circular transition: what is the circular economy maturity of Belgian ports? Sustainability 12(21):9269. https://doi.org/10.3390/su12219269
59. Campbell-Johnston K, ten Cate J, Elfering-Petrovic M, Gupta J (2019) City level circular transitions: barriers and limits in Amsterdam, Utrecht and The Hague. J Clean Prod 235:1232–1239. https://doi.org/10.1016/j.jclepro.2019.06.106
60. Ministerie van Algemene Zaken (2017) National agreement on the circular economy - Discussion document - Government.nl. https://www.government.nl/documents/discussion-documents/2017/01/24/national-agreement-on-the-circular-economy. Accessed 29 Jun 2023
61. De Bouw Campus, Provincie Zuid Holland (2020) Naar een ruintelijk en economisch model voor een circulair grondstoffen cluster. https://debouwcampus.nl/trajecten/circulair-grondstoffencluster. Accessed 29 Jun 2023
62. Hale TS, Moberg CR (2003) Location science research: a review. Ann Oper Res 123:15
63. van Ness A (2019) "Applied mathematics on urban space", in *The Mathematics of Urban Morphology: Modeling and Simulation in Science, Engineering and Technology*. Springer, Cham
64. Berghauser Pont M et al (2019) The spatial distribution and frequency of street, plot and building types across five European cities. Environ Plan B Urban Anal City Sci. 46(7):1226–1242. https://doi.org/10.1177/2399808319857450
65. L D'Acci, Ed (2019) *The mathematics of urban morphology*. Cham: Springer International Publishing, https://doi.org/10.1007/978-3-030-12381-9
66. Anselin L (2010) Thirty years of spatial econometrics: thirty years of spatial econometrics. Pap Reg Sci 89(1):3–25. https://doi.org/10.1111/j.1435-5957.2010.00279.x
67. Rosenthal SS, Strange WC (2003) Geography, industrial organization, and agglomeration. Rev Econ Stat 85(2):377–393. https://doi.org/10.1162/003465303765299882
68. Rikalovic A, Cosic I, Lazarevic D (2014) GIS based multi-criteria analysis for industrial site selection. Procedia Eng 69:1054–1063. https://doi.org/10.1016/j.proeng.2014.03.090
69. Randazzo L et al (2018) Landfill site selection for municipal solid waste by using AHP method in GIS environment: waste management decision-support in Sicily (Italy). Detritus 2(1):78. https://doi.org/10.31025/2611-4135/2018.13656
70. J Aldstadt (2010) "Spatial clustering," in *Handbook of Applied Spatial Analysis: Software Tools, Methods and Applications*, M. M. Fischer and A. Getis, Eds. Berlin, Heidelberg: Springer, 279–300. https://doi.org/10.1007/978-3-642-03647-7_15
71. Melo MT, Nickel S, Saldanha-da-Gama F (2009) Facility location and supply chain management – a review. Eur J Oper Res 196(2):401–412. https://doi.org/10.1016/j.ejor.2008.05.007
72. van Merrienboer S, Bastien T, Rondaij A, Rabbie J (2022) Kansen voor circulaire bouwhubs in de Provincie Zuid-Holland. https://www.tno.nl/nl/duurzaam/circulaire-waardecreatie/circulaire-economie-circulaire-waarde/

73. Provincie Utrecht (2021) Provincie Utrecht Beleidsvisie Circulaire Samenleving 2050. https://www.stateninformatie.provincie-utrecht.nl/documenten/Statenbrief/2020BEM182-02-1-Concept-Beleidsvisie-Circulaire-Samenleving-2050.pdf. Accessed 9 Jan 2022
74. Campbell JF, O'Kelly ME (2012) Twenty-five years of hub location research. Transp Sci 46(2):153–169. https://doi.org/10.1287/trsc.1120.0410
75. Tong D, Murray AT (2012) Spatial optimization in geography. Ann Assoc Am Geogr 102(6):1290–1309. https://doi.org/10.1080/00045608.2012.685044