Spatial approaches to a circular economy
Determining locations and scales of closing material loops using geographic data

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Spatial approaches to a circular economy

Determining locations and scales of closing material loops using geographic data

Dissertation

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chair of the Board for Doctorates
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by

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List of abbreviations

CE	Circular economy
EU	European Union
GHG	Greenhouse gases
GIS	Geographic information system
IS	Industrial symbiosis
LCA	Life cycle analysis
MFA	Material flow analysis
UM	Urban metabolism

Summary

Rapid urbanization and a growing world population has exerted unsustainable pressures on the environment, exacerbating climate change through unrestrained material usage and greenhouse gas (GHG) emissions. Since the turn of the century, transitioning to a circular economy (CE) has been seen by policy makers as a potential solution for resource scarcity and climate mitigation. Cities, which possess a high density of human activities, material stock, and waste production, are major contributors to emissions. This is especially true due to the concentration of construction activities in cities – the industry is responsible for 38% of CO2 emissions and 40% energy consumption globally. On the other hand, cities can also facilitate the implementation of circular strategies, thanks to increasing availability of data on space, people, and materials in cities.

While the importance of cities for the circular transition is recognized in literature, earlier studies and policy documents on “circular cities” focus on urban governance strategies. Scholars have therefore called for a deeper understanding of the spatial aspects of CE since the late 2010s, engendering the recent integration of spatial disciplines, such as urban planning, regional economics, and geography, into the study of CE. Moreover, the increasing availability of spatial data, especially on the location of material stocks and flows, provides an unprecedented opportunity to develop a data-driven understanding of where, and how far, materials should travel in a CE.

This research therefore asks the question, “what determines the locations and scales of closing material loops in a circular economy?” The question was answered in 5 chapters (chs. 3-7), using both quantitative and qualitative spatial analysis methods, as well as present- and future-oriented perspectives. The research scope moves from general to specific, with earlier chapters (chs. 3-6) analysing 10 material types for the whole country of the Netherlands, and later chapters (chs. 6-7) focusing on construction materials in the city of Amsterdam and its surrounding region. Two novel data sources were used throughout the research. Waste statistics from the Dutch National Waste Registry provided current locations of waste reuse; and a prediction dataset from the Dutch Environmental Assessment Agency provided locations for future supply for construction waste and future demand for construction materials.

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In chapter 3, a theoretical foundation for understanding locations and scales for closing material loops was constructed by identifying the drivers, barriers, and limitations of circular urban manufacturing - processes that produce goods using local secondary resources. By conducting a literature review and interviewing experts, it was found that there were several caveats to closing material loops at a local scale. Factors that determine the locations of circular urban manufacturers were identified from three perspectives: space, people, and flow.

In chapter 4, the factors affecting locations of waste reuse in the Netherlands were identified using spatial correlation. The previously identified space, people, and flow factors were translated into quantitative spatial factors that could affect the location of waste reuse. Correlations were found for flow and space-related factors, but not for people-related factors, which suggests that actors within the waste-to-resource supply chain tend to attract each other and cluster together to form agglomerations, and that locations of waste reuse are not related to attributes of the local population, such as local income, skills, or education.

In chapter 5, the location and scale of waste reuse clusters in the Netherlands were then identified using spatial statistical methods. This answered the main research question from a spatial econometric perspective, identifying industrial clusters for closing material loops. It was found that all the studied materials except for glass and textiles formed statistically significant spatial clusters. To determine the scale of spatial clustering, the grid cell sizes for data aggregation were varied, to find the cell size that had the strongest spatial clustering. The best fit cell size is ~7 km for materials associated with construction and agricultural industries, and ~20–25 km for plastic and metals.

In chapter 6, to answer the question from a spatial planning perspective, spatial parameters were identified for circular construction hubs - facilities that close material loops by collecting, storing, and redistributing demolition waste as secondary construction materials. Using the Netherlands as a case study, spatial parameters were extracted from two sources: Dutch governmental policy documents, 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 requirements for the four hub types were translated into a list of spatial parameters and analysis methods required to identify future locations - site selection, spatial clustering, and facility location.

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Finally, in chapter 7, spatial optimization was used to identify the optimal scale and location for circular timber hubs in Amsterdam and its surrounding region, answering the main research question from the perspectives of industrial ecology and logistics. The optimal scale was defined as a scale that is most cost effective, minimizing costs and maximizing emissions reductions through timber reuse. The optimal number of hubs for the study area was 29, with an average service radius of 3 km. The cost effectiveness was affected mostly by transportation and storage costs, while emissions savings had minimal effect.

As an overall conclusion, five tensions were identified for determining locations and scales for closing material loops, because of the diverse and sometimes misaligned spatial perspectives. The first three tensions are conceptual, addressing contrasting perspectives for defining closing material loops – as urban manufacturing or urban mining; for their locations – as clusters or hubs; and for the factors that affect locations and scales – as spaces, people, or materials. The final two tensions are methodological, addressing contrasting approaches to time – looking at the present or the future; and to methods – quantitative or qualitative.

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Samenvatting

Snelle verstedelijking en een groeiende wereldbevolking hebben een onhoudbare druk op het milieu uitgeoefend, waardoor de klimaatverandering is verergerd door ongebreideld materiaalgebruik en uitstoot van broeikasgassen (BKG). Sinds de eeuwwisseling wordt de overgang naar een circulaire economie (CE) door beleidsmakers gezien als een mogelijke oplossing voor grondstoffenschaarste en klimaatmitigatie. Steden, met een hoge dichtheid aan menselijke activiteiten, materiaalvoorraden en afvalproductie, leveren een grote bijdrage aan de uitstoot. Dit geldt met name vanwege de concentratie van bouwactiviteiten in steden – de industrie is verantwoordelijk voor 38% van de CO2-emissies en 40% van het energieverbruik wereldwijd. Anderzijds kunnen steden ook de implementatie van circulaire strategieën faciliteren, dankzij de toenemende beschikbaarheid van data over ruimte, mensen en materialen in steden.

Hoewel het belang van steden voor de circulaire overgang in de literatuur wordt erkend, richten eerdere studies en beleidsdocumenten over “circulaire steden” zich op stedelijke governance strategieën. Geleerden hebben daarom sinds de late jaren 2010 opgeroepen tot een dieper begrip van de ruimtelijke aspecten van CE, wat leidde tot de recente integratie van ruimtelijke disciplines, zoals stadsplanning, regionale economie en geografie, in de studie van CE. Bovendien biedt de toenemende beschikbaarheid van ruimtelijke gegevens, met name over de locatie van materiaal -voorraden en -stromen, een ongekende kans om een datagestuurd begrip te ontwikkelen van waar, en hoe ver, materialen zouden moeten reizen in een CE.

Dit onderzoek stelt daarom de vraag: “wat bepaalt de locaties en schalen van het sluiten van materiaalkringlopen in een circulaire economie?” De vraag werd beantwoord in 5 hoofdstukken (hfdst. 3-7), met behulp van zowel kwantitatieve als kwalitatieve ruimtelijke analysemethoden, evenals huidige en toekomstgerichte perspectieven. De reikwijdte van het onderzoek verschuift van algemeen naar specifiek, met eerdere hoofdstukken (hoofdstukken 3-6) die 10 materiaalsoorten analyseren voor het hele land van Nederland, en latere hoofdstukken (hoofdstukken 6-7) gericht op bouwmaterialen in de stad Amsterdam en de omliggende regio. Tijdens het onderzoek werden twee nieuwe gegevensbronnen gebruikt. Afvalstatistieken van het Landelijk Register Afvalstoffen gaven actuele locaties van hergebruik van afval; en een voorspellingsdataset van het Planbureau voor de Leefomgeving leverde locaties op voor het toekomstige aanbod van bouwafval en de toekomstige vraag naar bouwmaterialen.

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Eerst werd een theoretische basis voor het begrijpen van locaties en schalen voor het sluiten van materiaal lussen opgebouwd door de drijfveren, barrières en beperkingen van circulaire stedelijke productie - processen die goederen produceren met lokale secundaire grondstoffen - te identificeren. Door het uitvoeren van een literatuurstudie en het interviewen van experts werd vastgesteld dat er een aantal voorbehouden zijn aan het lokaal sluiten van materiaallussen. Factoren die de locaties van circulaire stedelijke producenten bepalen, werden geïdentificeerd vanuit drie perspectieven: ruimte, mensen en stroming.

De factoren die de locaties van afvalhergebruik in Nederland beïnvloeden, werden geïdentificeerd met behulp van ruimtelijke correlatie. De eerder geïdentificeerde ruimte-, mensen-, en stroming factoren werden vertaald in kwantitatieve ruimtelijke factoren die de locatie van afvalhergebruik kunnen beïnvloeden. Er werden correlaties gevonden voor stromings- en ruimte gerelateerde factoren, maar niet voor mensgerelateerde factoren, wat suggereert dat actoren binnen de afval-naar-grondstof keten elkaar tendentieel aantrekken en samenklonteren om agglomeraties te vormen, en dat locaties van afvalhergebruik niet gerelateerd zijn aan attributen van de lokale bevolking, zoals lokaal inkomen, vaardigheden, of opleiding.

De locatie en schaal van clusters van afvalhergebruik in Nederland werden vervolgens geïdentificeerd met behulp van ruimtelijke statistische methoden. Dit beantwoordde de hoofdonderzoeksvraag vanuit een ruimtelijk-economisch perspectief, door industriële clusters voor het sluiten van materiaal lussen te identificeren. Er werd vastgesteld dat alle bestudeerde materialen, met uitzondering van glas en textiel, statistisch significante ruimtelijke clusters vormden. Om de schaal van de ruimtelijke clustering te bepalen, werden de celgroottes voor data groepering gevarieerd, om de celgrootte te vinden die de sterkste ruimtelijke clustering had. De beste celgrootte is ongeveer 7 km voor materialen die geassocieerd zijn met de bouw- en landbouwindustrieën, en ongeveer 20-25 km voor plastic en metalen.

Om de vraag te beantwoorden vanuit een stedelijk-planning perspectief, werden ruimtelijke parameters geïdentificeerd voor circulaire bouwhubs - faciliteiten die materiaal lussen sluiten door sloopafval te verzamelen, op te slaan en opnieuw te distribueren als secundaire bouwmaterialen. Met Nederland als casestudy werden ruimtelijke parameters geëxtraheerd uit twee bronnen: Nederlandse overheid beleidsdocumenten, en interviews met bedrijven die circulaire hubs exploiteren. Er werden vier soorten circulaire bouwhubs geïdentificeerd: stedelijke mijnbouw hubs, industriële hubs, lokale materiaalbanken en ambachtelijke centra. De ruimtelijke vereisten voor de vier soorten hubs werden vertaald naar een lijst van ruimtelijke parameters en analysetechnieken die nodig zijn om toekomstige locaties te identificeren - locatiekeuze, ruimtelijke clustering en faciliteiten locatie.

Tot slot werd ruimtelijke optimalisatie gebruikt om de optimale schaal en locatie te identificeren voor circulaire houten hubs in Amsterdam en de omliggende regio, waardoor de hoofdonderzoeksvraag werd beantwoord vanuit de perspectieven van industriële ecologie en logistiek. De optimale schaal werd gedefinieerd als een schaal die het meest kosteneffectief is, waarbij kosten worden geminimaliseerd en emissiereducties worden gemaximaliseerd door hout te hergebruiken. Het optimale aantal hubs voor het studiegebied was 29, met een gemiddelde servicestraal van 3 km. De kosteneffectiviteit werd voornamelijk beïnvloed door transport- en opslagkosten, terwijl de besparingen op emissies minimaal effect hadden.

Als algemene conclusie werden vijf spanningen geïdentificeerd bij het bepalen van locaties en schalen voor het sluiten van materiaallussen, als gevolg van de uiteenlopende en soms niet op elkaar afgestemde ruimtelijke perspectieven. De eerste drie spanningen zijn conceptueel, waarbij contrasterende perspectieven voor het definiëren van het sluiten van materiaallussen – als stedelijke productie of stedelijke mijnbouw; voor hun locaties – als clusters of hubs; en voor de factoren die locaties en schalen beïnvloeden – als ruimtes, mensen, of materialen. De laatste twee spanningen zijn methodologisch, en richten zich op contrasterende benaderingen van tijd – kijken naar het heden of de toekomst; en naar methoden – kwantitatief of kwalitatief.

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摘要

在全球急速城市化與人口成長下，無節制的物質消耗與溫室氣體（GHG）的排放加劇了氣候變遷，為環境帶來無法承受的壓力。自邁入21世紀以來，政策制定者開始將循環經濟（CE）視爲緩解氣候變遷與資源短缺的可能方案。雖然城市為溫室氣體排放的禍首，但隨著與城市空間、社會和材料有關的數據日漸容易取得，城市亦成爲了促進循環經濟策略的集中地。

雖然早已有文獻提出循環經濟轉型的重要性，但由於早期關於“循環城市”的研究和政策文獻都側重於城市治理策略，因此自2010年代末，學者們便開始呼籲從空間的角度更深入地瞭解循環經濟。這促進了近期在循環經濟的研究中與城市規劃、區域經濟、地理學等空間學科的結合。此外，與材料的庫存和流動相關的空間數據也日漸便於取得。這讓學者們能夠前所未有地透過數據瞭解循環經濟中的材料該被運輸至什麽地方，至多遠。

因此，本研究探討的問題為：「在循環經濟中，封閉物質循環的位置和規模有哪些因素？」爲了找出解答，研究使用了定量和定性的空間分析方法來識別現有廢物循環設施集群的位置和規模，並為未來的循環設施提出建議。本研究使用了兩套新的數據來源，其中荷蘭國家廢物登記處提供了現有廢物循環設施的位置；而荷蘭環境評估局也提供了未來建築廢料與材料供需地點的預測。

本論文的第三至七章展示了研究成果。首先，第三章識別了城市循環製造商的動機、障礙和限制，並以此建立了理解物料循環位置和規模的理論基礎。文獻綜述和專家采訪的結果表明，近距離的物料循環有一些必須注意的事項。循環製造商的在城市中的位置取決於空間、社會，和物流三個因素。

第四章用了空間相關性 (spatial correlation) 來識別影響廢物循環地點的因素。在第三章識別的空間、人員，與物流三個因素被轉換成有可能影響廢物循環設施位置的定量空間因素。研究發現流量和空間因素之間存在相關性，而與人為因素沒有相關性。這表明在廢物回收的供應鏈中，回收商會彼此相吸而形成回收集群，但廢物循環設施的位置和當地人口的收入、技能、教育等屬性無關。

第五章從空間經濟學的角度解答本研究主要探討的問題，其中使用了空間統計的方法來識別荷蘭廢物回收工業集群的位置和規模。

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研究發現在廢物統計數據中的所有物料（除了玻璃和紡織品以外）都在數據上明顯地形成了空間群集。爲了判斷回收集群的規模，研究透過操縱數據聚合的網格單元大小以從空間上找出最佳單元大小。其中，建築與農業物料的最佳單元大小為約7公里，而塑料與金屬的最佳單元大小則爲約20-25公里。

第六章從空間規劃的角度識別了建築物料循環中心位置的空間參數。建築物料循環中心是一種通過收集、存儲，和重新分配將被拆除的建築廢料化爲二次材料的設施。本研究以荷蘭為案例從兩個來源提取空間參數，分別是荷蘭政府的政策文件，以及與循環中心負責人的訪談。研究識別了四類建築物料循環中心：城市礦業中心 (urban mining hubs)，工業中心 (industry hubs)，本地材料銀行 (local material banks) 和工藝中心 (craft centers)。這四種中心的空間需求被轉化成一系列的空間參數和分析方法，如場地選擇 (site selection)、空間聚類 (spatial clustering)，和設施分配 (facility location)等，以作爲決定未來循環中心位置的參考指標。

最後，第七章從工業生態學和物流的角度，使用了空間優選法 (spatial optimization) 來確認在阿姆斯特丹 (Amsterdam)以及周邊地區 木材循環中心的最佳規模和位置。本研究將最佳規模定義為：透過木材的循環最大限度地降低成本並最大限度地減少排放的規模。在研究範圍內的最佳循環中心數量為29個，平均服務三公里半徑內的地區，其中主要受到運輸和貯存成本的影響，而排放量的減少影響甚微。

第八章為本論文總結，列出了判斷物料循環設施位置和規模的五個分歧點。這些分歧點源於空間觀點上的出入。前三個矛盾點是概念性的：其一，該將“封閉物質循環的設施”定義爲城市中的製造業或采礦業？其二，該將其位置定義爲集群或是中心？其三，該將影響空間和規模定義爲空間、人為、或物料因素？最後兩個矛盾點是方法性的：其四，在時間上，該關注的是現在還是未來？其五，該使用定量或定性的研究方法?

1 Introduction

1.1 Circular economy

In an era increasingly defined by its simultaneous environmental, geopolitical, and economic crises, it has become evident that our traditional linear economy—characterized by a ‘take, make, and waste’ model—exerts unsustainable pressures on the environment, exacerbating climate change through greenhouse gas (GHG) emissions. Recent years have not only underscored the fragility of global supply chains, as evidenced by disruptions, e.g. during the COVID-19 pandemic and conflict between Russia and Ukraine, but also brought to the fore the growing issue of material scarcity (Dumée, 2022; Wuyts et al., 2020). This is particularly exacerbated by growing population and urbanization - over the past century, global population increased by a factor of ~4, usage of materials by a factor of ~10, usage of construction materials by a factor of ~42 (Deetman et al., 2020; Krausmann et al., 2017; Fishman et al., 2016).

The concept of a circular economy (CE) has gained traction among policy makers as a potential solution to these intertwined challenges. A CE aims to keep materials and products performing at their highest performance level using strategies such as recycling, remanufacturing, and reuse. The transition to such an economy necessitates an understanding of the locations and scales material flows—an endeavour for which we are increasingly equipped due to the rapid digitalization of society. Through harnessing the vast amounts of data now available, we have an unprecedented opportunity to generate insights into our economies’ spatial and material dimensions.

1.1.1 Theoretical development of circular economy

The paradigm of the circular economy (CE) has emerged from multiple academic disciplines, notably economics, sociology, environmental science, and industrial ecology. The following paragraphs provide a chronological review of the main academic theories that have contributed to the evolution of the topic. The first roots of the CE concept can be traced back to neoclassical economic theory, as early as the works of (Pigou, 1961) and later, (Boulding, 1966).

Pigou introduced the concept of negative externalities, positing that producers should bear the full cost of production, including environmental damages. Boulding pioneered the notion of “Spaceship Earth”, suggesting for us to view Earth as a spaceship with finite resources, advocating for their prudent use. Shortly after, in April 1968, Italian industrialist Aurelio Peccei and Scottish scientist Alexander King convene the first meeting of the Club of Rome, with the aim to understand the long-term consequences of growing global interdependence. Their project, “Predicament of Mankind”, was a pioneering work identifying the limits to growth in population and industrial capital.

The groundwork laid by Pigou, Boulding, and the Club of Rome was later expanded upon by the seminal work of Meadows et al., (1972) in their book “Limits to Growth”. This work investigated the dynamics of the global system, such as population growth, supplies of base materials, food production, industrial production and environmental pollution using computer models. It highlighted the impending repercussions of exponential economic and population growth with finite resources, thus providing an impetus for rethinking traditional linear economic models (van Timmeren, 2006). However, the model was criticized for its exclusion of scientific and technological advancements of its time, as well as not including critical social factors, such as education and employment (ibid).

By the late 20th century, literature connecting industrial systems to ecology began to emerge, bringing concepts that significantly contributed to the CE paradigm. Inspired by natural ecosystems, authors advocated for closed-loop systems where waste is minimally produced and serves as an input to another process. Key literature in this field include (Frosch & Gallopoulos, 1989), who proposed using waste from one industrial process as raw materials for another, and (Ayres, 1994), who proposed the metaphor of “industrial metabolism”, drawing an analogy between biological organisms and industrial activities. Parallel to this, the school of ecological economics (Costanza, 1992; Daly, 1991) challenged the neoclassical economic model by considering the economy as a subsystem of the finite biosphere, emphasizing the interdependence between ecological and economic systems.

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These early studies evolved into the theory of industrial ecology (T. E. Graedel & Allenby, 2003; Tibbs, 1993) which had a significant impact on the development of the CE paradigm, advocating for the minimization of waste and emissions through the redesign of production processes and products. Building upon this idea was the cradle-to-cradle approach (McDonough & Braungart, 2010), reinforcing the idea of waste as a resource; the performance economy (Stahel, 2010), which advocated for selling products as a service as a strategy to reduce material usage; and the blue economy (Pauli, 2010), which refers to the sustainable use of ocean resources for economic growth while preserving the health of the ocean ecosystem. What connects these concepts is their potential for achieving sustainable development and competitive advantage through the incorporation of ecological and social aspects into business and economic models.

Since the early 2010s, CE research has gained significant momentum, with publications increasing exponentially every year. Research has moved away from developing theoretical models, and is instead focusing on implementing these theoretical models in companies and business models (Corona et al., 2019; Gao et al., 2020). At the same time, The Ellen MacArthur Foundation emerged as a hub for businesses, policy makers, academia, and consultancies, helping to popularize CE research beyond academia (Ellen MacArthur Foundation, 2015a, 2015b). CE was integrated into governmental policy, most notably in China and the European Union (EU). In 2009, the Circular Economy Promotion Law was enacted in China (United Nations Environment Programme, 2008). In 2015, the European Union incorporated CE into policy by introducing its first circular economy action plan (European Commissions, 2015). This contributed to increased research funding and attention for CE research, both in China and in Europe.

In the late 2010s, the integration of spatial planning and CE became more prominent, with researchers developing new urban design tools to integrate CE concepts, such as resource stocks and flows, into landscape and urban design practice. This included developing new methods for mapping material stocks and flows, as well as making recommendations for future infrastructure based on resource scales and locations (Marin and De Meulder, 2018; Furlan et al., 2022). The development of the spatial dimension for CE is described in detail later in this chapter, in sections 1.2 and 1.3.

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1.1.2 Definitions and criticisms of circular economy

Although there is no consensus on its definition (Kirchherr et al., 2017), 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. Strategies for implementing a CE can be separated into three categories: slowing, narrowing, and closing resource loops (Bocken et al., 2016; Stahel, 2016). Slowing resource loops refers to extending the lifespan of products, decelerating the rate at which resources are converted into waste. Strategies to achieve this include repair, maintenance, remanufacturing, and upgrading. Narrowing resource loops refers to minimizing resource throughput in the production and consumption stages . It can be accomplished by enhancing material efficiency, decreasing energy consumption, and implementing approaches to dematerialization. Closing resource loops refers to the recycling and repurposing of products or materials at the end of their lifecycle, thereby keeping the resources within the economy instead of relegating them to waste.

While CE is frequently associated with sustainability, the relationship between the two concepts is disputed in literature. The difference between the concepts of sustainability and circular economy are two-fold. Firstly, the two concepts differ in terms of scope. On one hand, sustainability is focused on the so-called “triple bottom line” (Elkington, 1997), and the three pillars of sustainability: people, planet, and prosperity (United Nations, 2002). “People” included health, livability, freedom and freedom of choice; “planet” included purity and availability of energy, water, materials, waste and mobility; whereas “prosperity” included economic quality, including “profit”, affordability, honesty/reliability and transparency (van Timmeren, 2006).

Literature on sustainability tends to focus on the “planet” pillar, measuring the environmental impact of activities using tools such as Life Cycle Assessments (LCA) and Material Flow Analysis (MFA). On the other hand, CE seems to have a stronger focus on the “profit” pillar, with literature dominated by a business-focused narrative aiming at profit-generating solutions, often in the form of business models (Murray et al., 2017). Secondly, the two concepts differ in terms of aims: while the main aim of a circular economy is to minimize the use of primary raw materials and waste in a production system by slowing, narrowing, and closing material loops (Bocken et al., 2016; Stahel, 2016); sustainability addresses a multitude of issues such as greenhouse gas (GHG) emissions, land use, biodiversity loss, or toxicity, which may be prioritized differently according to the interest of researchers.

In a systematic literature review, (Geissdoerfer et al., 2017) categorized the relationship between CE and sustainability into three main types: ‘conditional’, ‘beneficial’, and ‘trade-off’. Some authors propose a ‘conditional’ relationship, stating that a circular economy is an essential condition or even the main solution for a sustainable system (Bocken et al., 2016; Lieder & Rashid, 2016). Other authors propose a ‘beneficial’ relationship, stating that circular economy is one of several solutions for fostering a sustainable system (Allwood & Cullen, 2012; Bocken et al., 2014). Finally, some authors also highlight a ‘trade-off’ relationship between circular economy and sustainability, describing, for example, the potential for circular systems to worsen the emission of greenhouse gasses and accelerate global warming (Allwood, 2014; Bocken et al., 2014). This dissertation takes the perspective of a circular economy having a ‘beneficial’ relationship with sustainability, meaning it is one of several potential solutions for fostering a sustainable system. For this research, a circular economy is therefore not a system that closes resource loops for its own sake. Instead, the goal of circular resource flows is to achieve sustainability.

While CE has gained substantial attention and acceptance in academic and policy discourse, it has also been the subject of various criticisms. Despite the growing body of literature, the CE concept lacks a universally accepted definition (Kirchherr et al., 2017). This ambiguity has led to the concept being applied inconsistently across different contexts and sectors, which limits the comparability of studies and impedes the development of a cohesive body of CE knowledge (Geissdoerfer et al., 2017). The CE transition is often portrayed as a universal solution to sustainability challenges. However, it is crucial to recognize that feasibility and effectiveness of CE strategies can vary across different geographical, technological, and sectoral contexts (Ghisellini et al., 2016). The CE emphasizes resource efficiency and waste reduction, but it can also potentially result in some unintended consequences. An example is the rebound effect, where efficiency gains lead to increased overall consumption, which can offset some environmental benefits of the CE (Sorrell, 2007). Finally, CE often focuses on technological innovation as the key enabler of circularity (Korhonen et al., 2018). A purely technological approach could overlook the necessity of fundamental changes in consumption patterns, cultural norms, and institutional structures for a successful CE transition.

While these criticisms of existing CE research cannot wholly be addressed by one dissertation alone, some criticisms can be partially addressed by narrowing down the research scope. Instead of proposing solutions for a CE as a whole, and can generally be applicable everywhere, this dissertation provides recommendations that are focused on a specific industry, strategy for implementing CE, and geographical and political context. The research scope will be addressed in sections 1.4 (goal and scope) and 2.1 (research context).

1.2 Two perspectives on space in circular economy research

In recent years, researchers have called for a deeper understanding of space in CE research (Bahers et al. 2022; Tapia et al. 2021; Schiller et al. 2014; Bourdin et al. 2021; Furlan et al. 2022), because the implementation of CE solutions has an obvious spatial expression. Circular companies form clusters to exchange materials and rely on existing physical infrastructure (such as road and water networks) to do so. Certain locations are more attractive for CE activities because they have a high accessibility to materials or skilled labor. Resource exchanges happen at different distances, depending on the value or physical characteristics of the resource, or on the business model of the company. In fact, some existing definitions of CE already point towards the relevance of scales, connectivity, and locations for a circular economy (Korhonen et al., 2018; Stahel, 2016).

The study of the spatial implications of CE can be separated into two partially overlapping groups - literature on “territorializing CE”, which primarily investigates how companies cluster together to exchange materials; and “spatially explicit urban metabolism (UM)”, which focuses on the location of material stocks and flows.

1.2.1 Territorializing circular economy

Tapia et al. (2021) provide 6 territorial factors in CE research - land-based, agglomeration, accessibility, technology, knowledge, and governance. Land based factors refers to land required to grow bio-based materials to satisfy future material demand, with hopes that the bio-based economy could be a driving development force in rural areas (European Commission, 2018; Philp & Winickoff, 2018). Agglomeration factors refers to the concentration of companies, consumers, materials, and infrastructure in urban areas that facilitate material exchanges between circular companies in industrial symbiosis programs (Domenech et al., 2019; Lombardi, 2017). High concentrations of materials in urban areas provide a sufficient ‘critical mass’ to achieve economies of scale and ensure financial sustainability of reclamation plants. Accessibility factors refers to companies’ level access to secondary materials, which relies on proximity to other companies providing by-products, or high concentrations of material stock. This is facilitated by areas around transportation hubs, such as ports, railway stations, or airports

(Malinauskaite et al., 2017). Technology factors refers to technologies that enable the implementation of CE processes, particularly digital technologies and industry 4.0 (Grillitsch & Asheim, 2018; Jawahir & Bradley, 2016; Nascimento et al., 2019). Knowledge factors refers to the availability of legal and technical capacity, skills, and information, as well as citizen awareness and alignment in circular business strategy development (Květoň & Kadlec, 2018; Marra et al., 2018). Governance factors contribute to creating the necessary conditions for CE ideas to be implemented in regions. These include strong institutional support for local circular businesses, as well as building inter-personal and inter-firm networks in a specific geographical area (Fernández-Esquinas et al., 2017; Kanda et al., 2019; Maillat, 1995; Niesten et al., 2017).

The theoretical roots of territorializing CE lie in the field of regional economics, especially in the study of agglomeration economies (Chertow et al., 2008; Tapia et al., 2021). The concept of agglomeration economies posits that industries tend to cluster in the same geographical area to minimize costs and maximize output, which leads to the formation of industrial districts, cities, and regional economies (Marshall, 1890). As a result, territories (nations, regions, cities) still exhibit differences in economic specialization and competitiveness, due to the influence of "factor conditions" on local economies (Porter, 1998).

Agglomeration economies relate to the co-location of firms within the same industry (localization economies), or in different and unrelated industries (urbanization economies) (Hoover, 1937). The study of localization economies was popularized by Porter (1998) in his research on business clusters and competitive advantage, where he found that localization economies depend not only on the cluster of firms but also surrounding consumers and institutions that support their growth. Urbanization economies, on the other hand, result from the concentration of economic activities that may accrue from the co-location of firms in diverse industries (Jacobs, 1969). Urban density and diversity allow for exchange of ideas, a large and diverse labor pool, business networks, and public goods like municipal services, public utilities, and transportation systems.

Agglomeration economies are facilitated by three mechanisms: sharing, matching, and learning (Duranton & Puga, 2003). The sharing mechanism refers to the benefits of sharing resources within a cluster, such as consumers, labor, and infrastructure, leading to increased specialization and reduced market demand uncertainty. The matching mechanism refers to better matches between a firm's specific needs and its environment, such as skilled workers, resources, or knowledge. The learning mechanism refers to the creation, exchange, and accumulation of knowledge within and across firms.

Circular strategies can also benefit from agglomeration economies. This can especially be seen in industrial symbiosis (IS) literature, which looks at how industries can cooperate to manage resource flows and improve overall environmental performance. The small city of Kalundborg in Denmark provides the best known case of IS in action. Here, business partners share groundwater, steam, and fuel, and exchange a variety of by-products, resulting in substantial economic and environmental benefits (Chertow, 2000).

IS activities can be differentiated into single-industry or multi-industry clusters. Single-industry clusters benefit from localization economies; most firms belong to a single industry, and use similar resources to make similar products, by-products, and residuals. Multi-industry clusters benefit from urbanization economies, where firms belong to diverse industries and exchange by-products. Density and diversity of firms, skilled labor, and resources allows for these exchanges. The three mechanisms for agglomeration economies (sharing, matching, and learning) are also relevant to IS clusters. By clustering together, companies can share utilities, and exchange by-products and knowledge (Chertow et al., 2008). IS has expanded to larger scales since Kalundborg, moving from the industrial site to the scale of regions and countries, with researchers debating the factors affecting resource exchange distances, as well as the optimal scale for IS (T. Graedel et al., 2019; Jensen et al., 2011; Lyons, 2008).

A similar perspective on scale can be found in CE literature, with researchers stating that CE operates at various organizational and geographical scales. CE has been implemented at three operational scales - micro, strategies for single companies; meso, strategies for eco-industrial parks; and macro, strategies for local, regional, and national economies (Ghisellini et al., 2016; Kalmykova et al., 2018). Different CE strategies have also been mapped onto corresponding geographical scales (Stahel, 2010). Product reuse is typically carried out at local and regional scales; repair and remanufacturing and local scales; and recycling at regional and global scales.

Like IS literature, CE research has started to investigate larger scales, explaining how CE can be implemented in cities and regions. This has led to an increased awareness of the importance of space in the circular transition, producing a new body of literature falling under the name of “circular cities” (Bucci Ancapi et al., 2022; Prendeville et al., 2018; Williams, 2019). Literature on circular cities can be separated into three main perspectives: space, people, and flows. The spatial (or urban planning) perspective investigates how urban planning and zoning strategies affect circular activity in cities (Ferm & Jones, 2016; Williams, 2019). The people (or urban governance) perspective investigates how municipalities and policy makers

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implement circular strategies at the city level (Fratini et al., 2019; Prendeville et al., 2018; Williams, 2019). The flows (or urban metabolism) perspective investigates the flows of materials and waste in a city, and how resource flows can be recirculated at the city level (Mulrow et al., 2017; Rosado & Kalmykova, 2019).

1.2.2 Spatially explicit urban metabolism

While ideas on territorializing CE focus on locations of companies and originates from regional economics and subsequently industrial symbiosis literature; spatially explicit urban metabolism offers an alternative perspective on the spatial implications of CE, focusing on locations of material stocks and flows, building on urban metabolism literature. Urban metabolism (UM) can be defined as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and elimination of waste” (Kennedy et al., 2007). While the definition already aims to integrate both technical and social perspectives, social scientists have still critiqued UM literature for neglecting the fact that, since human behaviour is determined by societal norms as well as natural laws, cities are not as simple as large biological ecosystems, and are driven by rules more complicated than predictable physical laws (McDonald et al. 2007; Henriquez & van Timmeren, 2017). That being said, physicists studying cities as complex systems have found that diverse characteristics of cities, including the amount of roads, crime, and companies, can be predicted using relatively simple power laws that govern the growth of cities (West, 2018).

The theoretical roots of UM stem from biology, where the concept of metabolism was originally used to describe living organisms. In 1935, ecologist Arthur Tansley expanded the term to include the material and energy from the construction of human settlements (Newman et al., 2009). This was followed by number of seminal quantitative UM studies: Weyl (1984) estimated the metabolism of Berlin by calculating the nutrient in- and out-flows of the city (Ledere & Kral, 2015), and Wolman (1965) estimated the in- and out-flow rates of a hypothetical American city of one million people using national data on water, food, fuel use, and production rates. Urban metabolism provides an alternative approach to traditional urban planning, where social, cultural, political and technical dimensions dominate over the biophysical dimension, instead synthesizing environmental and biological science into the urban planning discipline (Henriquez & van Timmeren, 2018). This builds upon Karl Marx’s conception of the “metabolic rift”, which describes the rupture in the metabolic interaction between humanity and the rest of nature due to capitalist agricultural production and the growing division between town and country (Foster, 2000).

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Urban metabolism studies examine a wide variety of flows in a city or region, and can be separated into two major schools of thought. The first school measures flows using energy equivalents, such as emergy or exergy; and the second school measures flows (such as water, materials, or nutrients) in terms of mass fluxes (usually in kg or tons) (Kennedy et al., 2011). While most urban metabolism literature illustrate the input of resources and output of waste, some papers examine cyclical urban metabolism or waste metabolism, where waste produced by a region is considered as a (secondary) resource or input for the city. Urban metabolism studies on waste recognize that, while products are produced from resource flow pathways, waste is processed by waste treatment and recycling pathways (Zhang, 2013).

In its early stages, urban metabolism treated ‘space’ as a system boundary for material flow analysis, rather than a topic of study. The first studies in urban metabolism were accounting exercises to calculate the total input, stock, and output of water, materials, nutrients, and waste of specific cities. There was less discussion on how the spatial aspects of the city (e.g. density, land use, proximity, accessibility) affected the location of these flows.

As urban metabolism developed, so did its approach to space, resulting in a variety of spatial approaches, which can be categorized into five types: political, territorial, socio-ecological, governance and planning, spatially explicit modeling (Bahers et al., 2022). The political approach deals with power relationships, land grabbing, resource exploitation and inequalities. The territorial approach deals with the organization of supply chains, territorial economy, and competitions. The socio-ecological approach deals with ecological economies of territories, locations of material stock accumulation, and society-nature interactions across spatial scales. The spatially explicit modeling approach deals with adding spatial parameters to existing environmental accounting methods such as material flow analysis, input-output models, and life cycle assessment. The governance and planning approach deals with sustainability grounded spatial patterns and infrastructure planning, which falls under efforts in sustainable urbanism, where urban planners and landscape architects incorporate flows of energy, water, materials, and people into design proposals (Brugmans & Strien, 2014; Remøy et al., 2019; Roggema, 2016; Tilly et al., 2014).

The increasing availability of spatial data and digital spatial analysis tools have made the spatially explicit modeling approach more feasible in the field of urban metabolism. Spatially explicit modeling approaches include mapping (geo-visualization) of stocks and flows, calculating eco-footprint of cities, incorporating insights into urban design and planning, and spatial modeling. Mapping of stocks includes visualization of the location of material stocks, most commonly construction material stock mapping; while mapping of flows include visualization of material flows, such as the work of (Furlan et al., 2020) on activity based spatial material flow analysis (Dijst et al., 2018). The study of ecological footprint of cities determines the amount of land required to provide a city with its resources and process its waste (Kennedy et al., 2007). Spatial modeling (or spatial statistics, spatial econometrics) combines statistics and geometry to create statistical spatial models of material flows, allowing researchers to make predictions for future scenarios and support spatial policy decisions (Dijst et al., 2018; Li & Kwan, 2018; Zhang et al., 2013). (Keirstead & Sivakumar, 2012) simulate urban resource demands using activity-based modeling, and (Zeyringer et al., 2015) estimate energy load profiles using spatial information on housing types and number of inhabitants. Other researchers have considered the interactions between an urban metabolism and the spatial distribution of land use and cover types (Huang et al., 2006; Huang & Chen, 2009; Idrus et al., 2008; Krausmann et al., 2003; Lee et al., 2009; Marull et al., 2010).

1.3 Two conceptualizations of locations and scales in a circular economy

The previous section provided an overview of spatial approaches to CE in existing literature. An important question that arises from study of space in CE is the issue of locations and scales. Where should circular strategies be implemented? And what determines suitable scales for closing material loops? The two spatial perspectives introduced in the previous section both provide answers to these questions. Literature on territorializing circular economy examines the locations and scales of **circular industrial clusters**, while literature on spatially explicit urban metabolism examines the locations and scales of **circular urban mining hubs**. The two perspectives' approaches to location and scale are summarized in the paragraphs below.

1.3.1 Circular industrial clusters

Circular industrial clusters are agglomerations of companies in close proximity to each other, sharing and exchanging resources for improved economic and environmental impact. The concept finds its roots in regional economics, agglomeration theory, industrial symbiosis, and circular cities.

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The connection between geographical location and circular industrial clusters can be found most prominently in industrial symbiosis (IS) literature. The issue of location is already implicitly addressed in early IS literature, which emphasized on the importance of geographical proximity between companies exchanging resources, suggesting that companies conducting industrial symbiosis should be in the same location, such as an eco-industrial park (Chertow, 2008). By studying the successes and failures of IS case studies, researchers identified the local environmental factors that facilitated resource exchanges, such as accessibility to nearby infrastructure, skilled labor, or by-products. Later studies addressed the issue of location more explicitly, by identifying the locations of industrial symbiosis clusters on a map, using surveys and interviews (Domenech et al., 2019), or using spatial statistical methods to analyze spatial data on industrial facilities (Mendez Alva et al., 2021).

More recently, the study of circular industrial clusters have been implemented in port regions. Ports have a number of unique characteristics that are beneficial to the CE transition: they house a diverse range of industrial activities allowing for possibilities for resource exchange, they are a logistics hub for a significant amount of material flows, and they are often close to urban areas, and thus have easy access to skilled labor and knowledge networks. Existing research has provided case studies on how port authorities have integrated CE into their strategies, and identified future scenarios for circular clusters in port regions that vary in purpose, users, scale, and resources exchanged (Architecture Workroom Brussels, 2021; Gravagnuolo et al., 2019; Haezendonck & Van den Berghe, 2020).

In terms of scale of material exchanges, industrial symbiosis literature provides debate on the distances that materials travel, as well as the benefits and trade-offs of organizing resource flows at the local, regional, national, or global scale. For some studies, the exploration started as a response to a common implicit assumption that the optimum scale for a closed material loop is the local scale. This was seen in earlier literature in industrial ecology, and strengthened by the empirical findings of Kalunborg, Denmark (Chertow, 2000). However, there is no a priori reason to expect that any one spatial scale is most suitable for closing loops (Lyons et al., 2009).

While the local scale is often assumed to be the optimum scale for closing material loops due to low transportation emissions, multiple studies have found that transportation emissions are negligible when compared to emissions reductions from material reuse (Kreidenweis et al., 2016; Park & Gupta, 2015; Russell & Allwood, 2008). It is generally agreed that there is no universal optimal scale, but the scale of closing material loops depends on characteristics of the material (such as weight, volume, or value), or profitability of the material exchange (Lyons, 2008). Research has shown cases of successful waste-to-resource exchanges at multiple scales - local (2-5 km), within the same industrial park (Chertow, 2008; Lambert & Boons, 2002) or even the same facility (Mulrow et al., 2017); regional (30-50 km), within the same metropolitan region or province (Jensen et al., 2011; Lyons, 2008; Sterr & Ott, 2004); and global, with resource exchanges across international borders (T. Graedel et al., 2019).

Most studies on circular industrial clusters use qualitative methods, such as surveys, interviews, and case studies, to identify the locations and scales for closing material loops. However, relatively few studies are exploring the usage of qualitative methods, such as spatial statistical analysis, to answer the same questions (Jensen et al., 2011, 2016). This is a missed opportunity, as more spatial data related to circular industrial clusters is becoming openly available and easily accessible. Examples include census data, or data on the locations of infrastructure, industrial activities, and land use. Moreover, case studies for circular industrial clusters have primarily focused on smaller scale clusters, where resources are exchanged within the same industrial site or even the same facility. This has led to a bias in focus towards small-scale, local, and urban material flows, while flows at the regional, national, and global scale are relatively less understood.

1.3.2 Circular urban mining hubs

Circular urban mining hubs refer to facilities that collect, store, and redistribute secondary materials, located in areas with sufficient density of materials, and high accessibility to transportation networks. The concept builds on urban mining literature, where existing material stock in cities (most often in buildings or infrastructure) is seen as part of an “urban mine”, containing secondary materials that could be used to produce future products in a circular economy (Brunner, 2011; Cossu & Williams, 2015; Krook & Baas, 2013; Zhang et al., 2019).

Urban mining literature addresses the issue of location by mapping existing material stock in urban areas. Maps are produced at high spatial resolution, using spatial aggregation units as small as individual buildings (Deetman et al., 2020; Sprecher et al., 2021; Stephan & Athanassiadis, 2017, 2018; Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009; van Oorschot et al., 2023). The location and amount of material stocks is estimated by combining cadaster data with material intensity estimations. Cadaster data comes from a cadastral registry, which is a public record on the location, value, boundaries, and square-footage of real estate property in an administrative region, such as a city, province, or country. Material intensity refers to the amount of materials embedded in buildings or infrastructure, measured in kilograms per square meter. Material intensity data is based on “archetypes” of

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buildings according to their age, usage, and size; and the amount of materials per square meter associated with each building archetype. By combining kadaster and material intensity data, researchers can create highly detailed maps on the location and amount of materials embedded in a city, that could hypothetically be reused in the future when buildings get demolished.

Scholars have developed increasingly accurate methods for estimating locations and amount of material stock. This includes improving the accuracy of material intensity estimations with building demolition experts (Sprecher et al., 2021) or image recognition (Raghu et al., 2022), and estimating when material will become available in the future using probability distributions (Heeren & Hellweg, 2019). Complimenting the mapping of material stocks is the mapping of material flows, where the flow of secondary resources can be mapped using waste statistics data (Furlan et al., 2020; Sileryte et al., 2022).

Using increasingly accurate information from urban mining maps, researchers have also started to explore the scale for closing material loops, to understand whether secondary resources should be collected and exchanged at the the neighborhood, city, regional, or national scale. This can be done by estimating the match between future supply and demand of secondary materials within a specified geographical area. For example, (Verhagen et al., 2021) estimated that, within the municipality of Leiden in the Netherlands, the future supply and construction waste does not satisfy the future demand for construction materials. More recently, other researchers have used optimization algorithms from logistics literature to find the optimal service areas of facilities, balancing the trade-off between lower transportation costs for smaller scales, and better supply and demand matching at larger scales (Hodde, 2021; van Oorschot et al., 2023; Xue et al., 2017).

Compared to literature on circular industrial clusters, studies on urban mining have a much stronger affinity with quantitative spatial data and analysis methods. While most studies have focused on developing increasingly accurate representations of material stock locations, more recent studies have started to develop recommendations for infrastructure and spatial design interventions (Furlan et al., 2020; Xue et al., 2017; Hodde, 2021). The availability of spatial data on material stocks and flows presents an opportunity to use quantitative spatial analysis methods to propose the future locations and scales of circular urban mining hubs, moving from describing where materials stocks and flow are currently, to where they should be in the future. Moreover, because of the focus on providing a snapshot of the current state of material stocks and flows, most studies lack an understanding of time. This leads to a rather static view of urban mining, and does not take into account how the locations of material stocks, flows, and infrastructure could change in the future.

1.4 Research goal and scope

To summarize this chapter, the research in this dissertation was conducted in response to the challenge of resource scarcity and the unprecedented opportunity provided by the emergence of large spatial datasets on material stocks and flows, which allows for a deeper understanding on spatial aspects of the circular economy. In recent years, scholars have explored locations and scales in CE from two perspectives, conceptualizing locations for closing material loops as circular industrial clusters, and circular urban mining hubs. Currently, not many studies use quantitative spatial data and analysis methods to identify the locations and scales of closing material loops. Of the studies that use quantitative methods, not many have gone beyond mapping the current state of material stocks and flows to provide recommendations for future infrastructure.

The goal of this research is therefore to take advantage of available spatial data and analysis methods to find out what determines locations and scales of closing material loops in a CE. To achieve this goal, this research aims to:

1. **Enhance our spatial understanding of CE by developing a theoretical framework to determine locations and scales of closing material loops,**

2. **Understand the current spatial state of CE by finding locations and scales for closing material loops in the present, and**

3. **Develop spatial recommendations for CE by proposing locations and scales for closing material loops in the future**

While CE strategies can include slowing, narrowing, and closing material loops, this research will focus on the third category – closing material loops by reusing waste as a resource. This is because currently available spatial data, such as waste statistics and maps of urban material stock, can contribute most directly to strategies related to closing material loops, such as waste recycling and reuse. Within the wide variety of spatial perspectives introduced in sections 1.2 and 1.3, this research will focus on quantitative spatial analysis methods, as this allows us to take full advantage of the spatial datasets that have been recently made available; as well a spatial planning perspective, which investigates the spatial implementation of CE strategies at larger geographical scales.

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This research will focus on the role of companies and governmental organizations, and how they can use spatial data to make decisions in a CE, rather than exploring the role of citizens and bottom-up communities. This focus is best illustrated by the work of Bauwens et al. (2020), who presented four scenario narratives for the future of CE, each taking a position on two pairs of opposing approaches: centralized versus decentralized governance, and high-tech versus low-tech innovations.

The question of centralized versus decentralized governance refers to the broader debate of democratic and authoritarian environmentalism. Authoritarian environmentalism, associated with centralized governance approaches, believes that centralized political leadership by experts produces optimal outcomes compared to more participatory approaches. Democratic environmentalism, associated with decentralized governance approaches, have higher involvement of small-scale, local communities in political and economic decision-making, and is often seen as a way to deepen and strengthen democracy.

The question of high- versus low-tech innovation refers to the tension between more techno-pessimistic and more techno-optimistic views regarding the environmental and social impacts of technologies. Techno-optimists aim to decouple a growth oriented consumer economy from environmental impact using technological innovation and market mechanisms. Techno-sceptics, on the other hand, emphasize the need to move away from resource-intensive and consumerist lifestyles, adopting “low-tech” innovations to reduce resource use.

As seen in Figure 1.1 below, the two pairs of opposing approaches result in four future scenarios: “planned circularity”, “circular modernism”, “bottom-up sufficiency”, and “peer-to-peer circularity”. This research aligns most closely with “circular modernism”, a narrative which relies on centralized governance and high-tech innovations.

The research scope of this dissertation moves from general to specific. The geographical scope starts from studying the Netherlands as a whole, and ends with Amsterdam and its surrounding region. The scope of materials studied starts with 10 waste material types from the Dutch waste registry, and ends with a focus on construction materials.

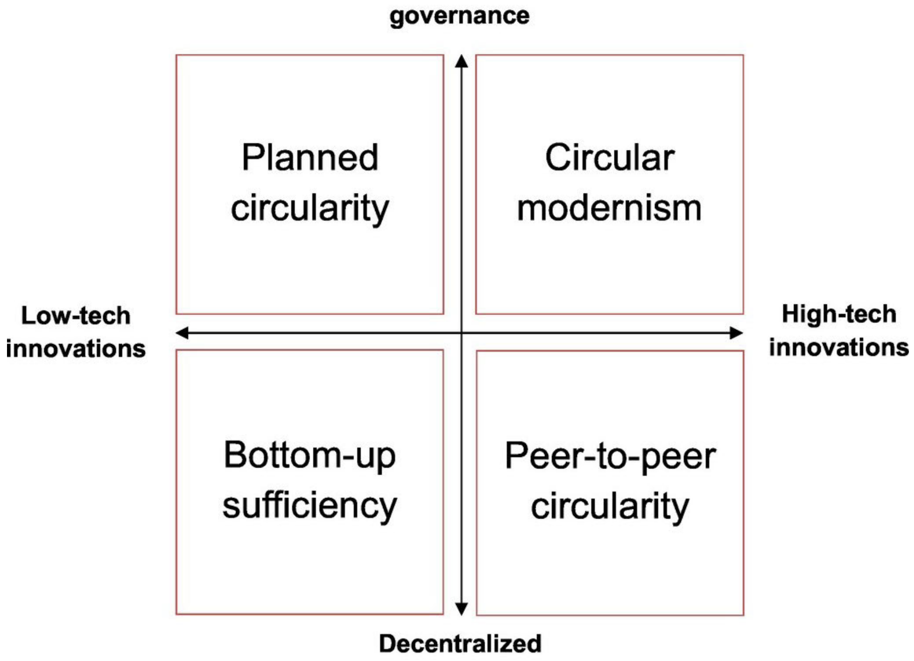

FIG. 1.1 Four scenarios for circular futures (Bauwens et al., 2020)

2 Research design

This chapter will provide an overview of the research design for this research. Firstly, the research context is introduced, justifying why the Netherlands was chosen as the focus on this dissertation. Then, the main research question is introduced, together with sub research questions that correspond to chapters 3-7. Then the methodology of this dissertation is introduced as mixed methods approach, combining quantitative and qualitative methods, as well as present and future perspectives. Finally, a summary of data and methods used per chapter are presented.

2.1 Research context

This research will focus on the Netherlands as a case study for developing a deeper spatial understanding of CE. The Netherlands is an early adopter of CE, and has made efforts to integrate CE practices into policy since the early 2000s. Recognizing the need for sustainable waste management, the Dutch government introduced the Landelijke Afvalbeheerplan in 2003 (Dutch Ministry of Infrastructure and Water Management, 2003), aiming to recover as much waste as possible and improve recycling practices. The pivotal moment in the integration of the circular economy into Dutch policy came in 2016 with the publishing of “Nederland Circulair in 2050” (Dutch Ministry of Infrastructure and Water Management & Dutch Ministry of Economic Affairs, 2016). This government-wide program detailed the aim to transition to a fully circular economy by 2050, with an interim target of a 50% reduction in the use of primary resources by 2030. The Dutch government then concluded the Raw Materials Agreement (Dutch Ministry of Infrastructure and Water Management, 2017), which represents a collaborative effort with businesses, governments, and NGOs to ensure a more efficient use of raw materials. To further operationalize the goals of the 2016 strategy, five transition agendas were published in 2018 detailing sector-specific approaches for a circular economy. These agendas cover Biomass and Food, Plastics, Manufacturing, Construction, and Consumer Goods (Dutch Ministry of

Infrastructure and Water Management, 2022). A timeline for the development of CE policy in the Netherlands can be found on the Dutch government website[1].

CE goals at the national level have been translated into concrete actions at the provincial and municipal level. Provinces including North Holland, South Holland, Utrecht, and North Brabant have developed policy visions and action plans for implementing CE, emphasizing the need for collaboration between businesses, knowledge institutions, and governments (Provincie Noord Holland, 2021; Provincie Utrecht, 2021; Provincie Zuid Holland, 2019; Royal Haskoning DHV, 2020). The same can be seen in a number of Dutch municipalities, producing “circular citiy” policy documents that highlight local stakeholders and resources that could facilitate the circular transition (Campbell-Johnston et al., 2019; City of Amsterdam & Circle Economy, 2020; Gemeente Den Haag, 2018; Metabolic et al., 2018).

More recently, CE has been mentioned in spatial policy documents. This can most prominently be seen in environmental visions (omgevingsvisie) at the national, provincial, and municipal level (Dutch Ministry of the Interior and Kingdom Relations, 2020; Gemeente Amsterdam, 2021; Provincie Noord Holland, 2018; Provincie Zuid Holland, 2021). However, compared to other priorities such as energy and transportation, the integration of CE into spatial policy is still relatively underdeveloped. In fact, when explaining the CE transition, the national environmental vision states that “the consequences of this transition on transport flows, use of space, the environment and security remain uncertain.” (Dutch Ministry of the Interior and Kingdom Relations, 2020)

Companies have also developed new circular strategies in response to the prioritization of CE in Dutch policy. More specifically for this research, organizations are contributing to the CE transition from a spatial perspective. This includes port authorities developing their real estate into circular clusters (Architecture Workroom Brussels, 2021; Gravagnuolo et al., 2019), as well as demolition companies turning their storage facilities into circular construction hubs (Tsui et al., 2023). Circular strategies have also been integrated into the development of neighbourhoods and areas, allowing urban planners to bridge the gap between large scape circular policy goals and individual circular building projects (Weber, 2019; Van den Berghe and Vos, 2019).

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[1] https://www.government.nl/topics/circular-economy/circular-dutch-economy-by-2050

In addition to having CE high on the policy agenda, the Netherlands has high quality and availability of spatial data, especially on material stocks and flows. This includes high spatial resolution data on locations of waste flows from the Dutch Waste Registry (Sileryte et al., 2022), as well as material embedded in the current building stock (van Oorschot et al., 2023). Given the integration of CE in policy and the availability of spatial data on material stocks and flows, the Netherlands provides a promising context for studying the spatial aspects of the circular transition.

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2.2 Research questions

Based on the research goals and context described in the previous chapter, the main research question is:

What determines suitable locations and spatial scales for closing material loops in a circular economy?

The following sub research questions, associated with chapters 3-7 in this dissertation, investigate different aspects of the main research question. The closing of material loops is conceptualized differently throughout the research – as circular urban manufacturers, waste reuse clusters, and circular construction hubs.

1. **Theoretical framework for closing material loops (chapter 3)**
   a. Does urban manufacturing contribute to a circular economy in cities, and if so, how?
   b. What are the drivers and barriers to circular urban manufacturing?

2. **Factors determining locations of waste reuse clusters (chapter 4)**
   a. Does the location of waste reuse follow a spatial pattern?
   b. What is the correlation between the amount of secondary resources received by waste reusers in the construction industry, and the space, people, and flow-related factors?

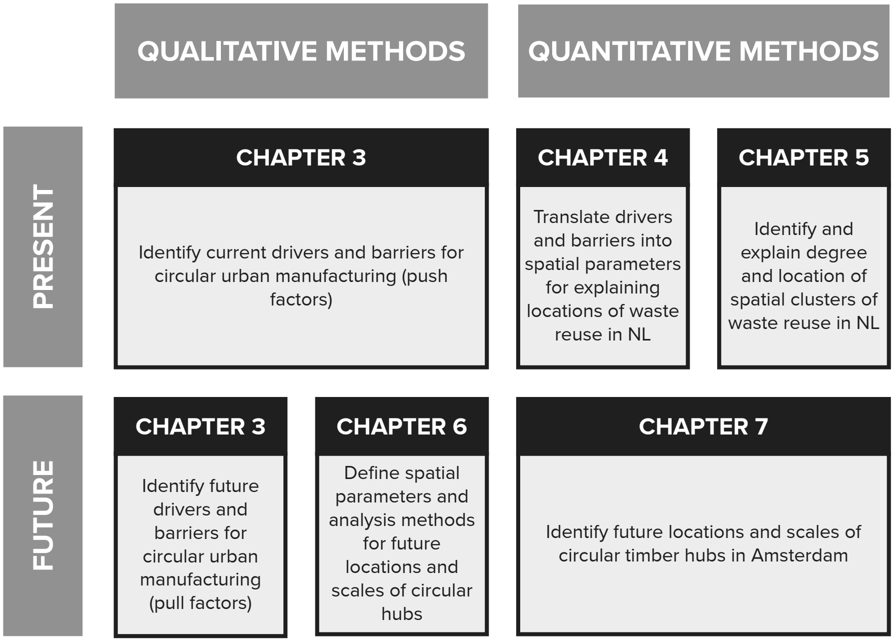
3. **Spatial clustering analysis of waste reuse (chapter 5)**
   a. What is the degree, scale, and location of spatial clustering of waste reuse locations in the Netherlands?
   b. What are the potential insights and caveats of identifying hotspot locations of waste reuse locations in the Netherlands?

4. **Spatial parameters for circular construction hubs (chapter 6)**
   a. What are the spatial parameters for locating circular construction hubs in the Netherlands?
   b. What are the spatial data and analysis methods required to identify the potential locations of circular construction hubs in the Netherlands?

5. **Spatial optimization of circular construction hubs (chapter 7)**
   a. What is the optimal scale and locations for circular timber hubs in the Metropolitan Region of Amsterdam?

2.3 Methodology

This dissertation is based on 5 academic articles (chapters 3-7), using both quantitative and qualitative spatial analysis methods to answer the main research question. Together, the chapters contribute to a better understanding of spatial characteristics of the current state of CE in the Netherlands, as well as provide spatial planning recommendations for the locations and scales closing material loops in the future. Figure 2.1 below provides an overview of the 5 articles, which can be categorized into two methodological approaches, qualitative and quantitative; and two perspectives, studying present conditions and future scenarios.



	QUALITATIVE METHODS		QUANTITATIVE METHODS	
PRESENT	CHAPTER 3 Identify current drivers and barriers for circular urban manufacturing (push factors)		CHAPTER 4 Translate drivers and barriers into spatial parameters for explaining locations of waste reuse in NL	CHAPTER 5 Identify and explain degree and location of spatial clusters of waste reuse in NL
FUTURE	CHAPTER 3 Identify future drivers and barriers for circular urban manufacturing (pull factors)	CHAPTER 6 Define spatial parameters and analysis methods for future locations and scales of circular hubs	CHAPTER 7 Identify future locations and scales of circular timber hubs in Amsterdam	

FIG. 2.1 Overview of research chapters. The research is based on 5 academic articles (chs. 3 - 7). Together, the articles cover both quantitative and qualitative methods (columns in the diagram), and present and future perspectives (rows in the diagram).

2.3.1 Mixed methods research

The research design of this dissertation can be considered as mixed methods research, which integrates both quantitative and qualitative methods into a single study, allowing for a more robust and nuanced analysis of complex phenomena (Maxwell & Loomis, 2010; Plano Clark & Badiee, 2010).

Literature has identified several reasons for using mixed methods (Plano Clark & Badiee, 2010), many of which are highly relevant to the topic of determining locations and scales for closing material loops. Answering the research question using methods from different perspectives allows for a fuller understanding of the locations and scales of closing material loops, especially when divergent perspectives are compared and contrasted. Using both qualitative and qualitative spatial analysis methods allow for the compensation of each method's weaknesses – qualitative methods (chs. 3, 4, 5) create clear research directions by understanding the current context and future trends for closing material loops, whereas quantitative methods provide concrete validations (chs. 4, 5) and measurable future impact predictions (ch. 7).

Mixed methods research can be separated into three types – parallel, sequential, and conversion mixed method designs (Plano Clark & Badiee, 2010). In parallel designs, two sets of data (one qualitative and one qualitative) are simultaneously and independently collected and analyzed. In sequential designs, the second round of data collection and analysis is based on the results of the first round. In conversion designs, one type of data is converted to another and re-analyzed to get more credible answers. This dissertation uses a mix of sequential and conversion methods. The qualitative drivers, barriers, and preferences for locations and scales identified in chapters 3, 4, and 6 were converted into quantitative spatial parameters for spatial analysis in chapters 4, 5, and 7.

Triangulation is an important concept to test the validity of research. Literature has identified 5 types of triangulation: data, investigator, theory, methodological, and environmental (Guion et al., 2011); and this dissertation uses 3. Data triangulation involves using different sources of information. This dissertation uses both quantitative spatial data (from the Dutch Waste Registry and the Dutch Environmental Assessment Agency), as well as qualitative data from interviews and document reviews. Theory triangulation involves the use of multiple perspectives to interpret a single phenomenon. This dissertation combines the perspectives of industrial ecology, waste management, and economic geography to interpret the locations and scales of closing material loops. Methodological triangulation involves the use of multiple (qualitative and quantitative) methods to answer a research question. This dissertation uses multiple methods to determine the locations and scales.

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The 5 chapters of this dissertation can be categorized into two methodological approaches, qualitative and quantitative; and two perspectives, studying present conditions and future scenarios, as seen in Figure 2.1. The following two sections will further explain how the underlying philosophical stances of the two methodological approaches and perspectives, and how they are combined throughout the dissertation.

2.3.2 Combining qualitative and quantitative methods

Quantitative and qualitative methods are supported by opposing philosophical stances - positivist and constructivist (Maxwell and Loomis, 2010; Creswell, 1994; Guba and Lincoln, 1989). By combining quantitative and qualitative methods, this research addresses the limitations of both opposing stances.

Quantitative methods are positivist, believing that there is an objective reality that exists independently of human perception, and that this reality can be understood through the objective observation, measurement, and experimentation or quantitative data. Positivist methods are replicable, generalizable, and rigorous. However, positivist methods tend to simplify complex phenomena by reducing them to measurable variables, overlooking subjective aspects, potentially leading to a biased understanding. Quantitative methods are used in chapters 4, 5, and 7.

Qualitative methods are constructivist, emphasizing that knowledge is not discovered but rather actively constructed by individuals based on their subjective experiences, and that different interpretations of reality can coexist. Constructivist methods emphasize the role of social and cultural contexts, providing a comprehensive understanding of how these contexts shape knowledge and reality. However, constructivist methods rely heavily on interpretation, which can introduce subjectivity and potential biases. Moreover, findings may be highly context-dependent and may not be easily generalizable. Qualitative methods are used in chapters 3 and 6.

The qualitative chapters (chs. 3, 6) compensate for the limitations of the quantitative chapters (chs. 4, 5, 7), and vice versa. Aspects overlooked in the quantitative chapters, such as the complexity of determining locations and scales resulting from diverse stakeholder perspectives, are addressed by expert interviews and document reviews in the qualitative chapters. Aspects overlooked by the qualitative chapters, such as the lack of objectivity and generalizability of opinions on spatial CE, are addressed by spatial statistical methods in the quantitative chapters.

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2.3.3 Combining present and future perspectives

Present and future perspectives are associated with opposing philosophical stances – descriptive and normative (Maxwell and Loomis, 2010; Creswell, 1994; Guba and Lincoln, 1989). By combining both perspectives, this research addresses the limitations of both opposing stances.

In this dissertation, chapters studying the present (chs. 3, 4, 5) are descriptive, describing or explaining phenomena as they are observed without making value judgments. Descriptive methods make objective and unbiased observations based on empirical evidence. However, examining existing phenomena limits our perspective to the present and past, and provides limited guidance on what to do in the future.

Chapters with a future perspective (chs. 3, 6, 7) are normative, making judgments based on a particular set of values, principles, or norms. Normative methods provide an aspirational vision, imagining ideal or preferred future states, allowing for the exploration of future paradigms or scenarios that don't yet exist. However, normative methods are subjective by nature, reflecting the values and perspectives of a limited number of individuals, introducing biases.

The "present" chapters (chs. 3, 4, 5) compensate for the limitations of the "future" chapters (chs. 3, 6, 7), and vice versa. Aspects overlooked in the "present" chapters, such as a limited number of future perspectives on locations and scales for CE, are addressed in the "future" chapters. Aspects overlooked in the "future" chapters, such as subjective values and perspectives of stakeholders, are addressed in the "present" chapters.

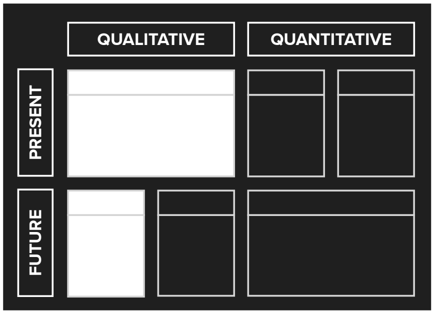
2.3.4 Data and methods

The initial impetus for this research was to take advantage of the recent proliferation of spatial data that could potentially contribute to circular economy research. This dissertation utilizes two novel data sources on the Netherlands: chapters 4 and 5 use the Dutch National Waste Registry dataset on locations of waste production, processing, and reuse (Dutch Ministry of Infrastructure and Water Management, 2019; Sileryte et al., 2022); and chapter 7 uses the Dutch Environmental Assessment Agency dataset on locations of future supply and demand of secondary construction materials (van Oorschot et al., 2023). More commonly used spatial data is also used throughout the research, including the Dutch Provinces Association dataset on locations of industrial estates (Interprovinciaal Overleg (IPO), 2022), the Statistics Netherlands dataset on census information (Centraal Bureau voor de Statistiek, 2023), and OpenStreetMap data on locations of street networks and major transit stations (OpenStreetMap contributors, 2017).

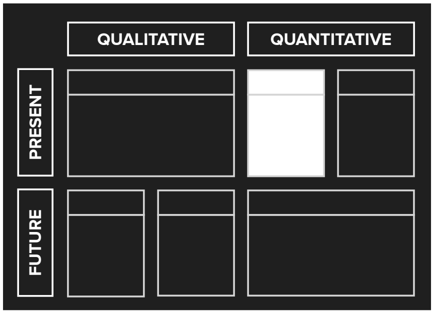
Well established spatial data analysis methods are adapted from various academic disciplines, including economic geography, waste management, industrial ecology, and logistics management. The research scope of this dissertation moves from general to specific as the chapters progress, with each chapter building upon the findings of the previous one. The geographical scope starts from studying the Netherlands as a whole, and ends with Amsterdam and its surrounding region. The material scope starts from studying 10 material types from multiple industries, and ends with a focus on construction materials. A detailed summary of methods and data used per chapter can be found in the following section (2.4).

2.4 Summary of methods and data per chapter

This dissertation uses both qualitative and quantitative methods to determine locations and scales for closing material loops for a circular economy in the Netherlands, addressing both present- and future-oriented perspectives. The following paragraphs provide an overview of the methods and data used in each chapter.

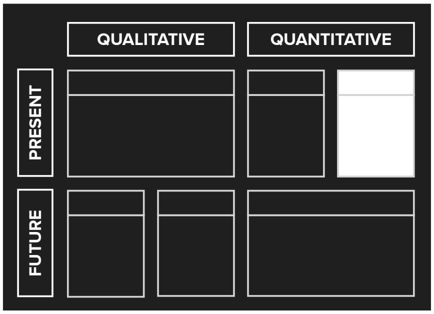


Chapter 3 uses qualitative methods, and addresses both present and future-oriented perspectives. The chapter develops a theoretical framework for closing material loops in a CE by identifying drivers and barriers for circular urban manufacturers – organizations that manufacture products using locally available waste in urban areas. By conducting literature review and expert interviews, the drivers and barriers are identified from three perspectives – spatial-, social-, and material-related. Both present and future factors are identified – some factors already have a concrete impact on closing material loops today, while other factors will more likely happen in the future, in connection to larger global trends such as resource nationalism and the global pandemic. The drivers and barriers provide a first understanding of what determines the locations and scales of closing material loops in a CE.

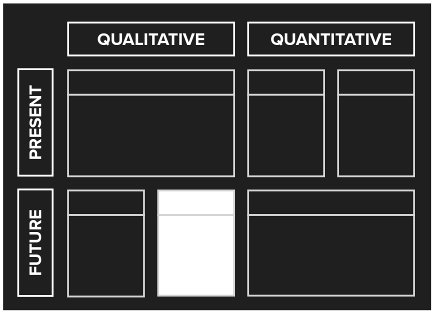


Chapter 4 uses quantitative methods and is present oriented. It provides an understanding of the present state of closing material loops in the Netherlands. First, the spatial, social, and material-related drivers and barriers identified from chapter 3 are translated into quantitative spatial characteristics that could potentially explain the locations of material loop closing activities. Then, correlations between the spatial characteristics and waste reuse locations in the Netherlands are calculated. Data for spatial characteristics are extracted from Statistics

Netherlands (Centraal Bureau voor de Statistiek, 2023) and OpenStreetMap (OpenStreetMap contributors, 2017), and locations of waste reuse are extracted from the Dutch Waste Registry dataset (Dutch Ministry of Infrastructure and Water Management, 2019; Sileryte et al., 2022). By studying the quantitative correlations using empirical waste reuse location data, the chapter validates the factors previously identified by literature and experts in chapter 3.



Chapter 5 uses quantitative methods and is present oriented. It identifies the present locations and scales of waste reuse clusters in the Netherlands for 10 material types using the Dutch Waste Registry dataset. Locations are identified using spatial auto-correlation, a statistical method used to identify statistically significant spatial hot spots in spatial data. Scales are determined by varying the cell sizes used to aggregate the waste reuse locations. For each material, the cell size that resulted in the highest amount of spatial clustering is deemed the "best fit" cell size, which provides an indication of the scale of spatial clusters. Together with the results of chapter 4, this chapter provides an understanding of the current condition in terms of the scales and locations of waste reuse activities in the Netherlands.



Chapter 6 uses qualitative methods and is future oriented. In the chapter, quantitative spatial parameters and spatial analysis methods are identified for determining the locations and scales of circular construction hubs - facilities that close material loops by collecting, storing, and redistributing demolition waste as secondary construction materials. Parameters and analysis methods are extracted using two methods: review of Dutch governmental policy documents, and semi-structured interviews with circular construction hub operators. The spatial parameters are categorized into four perspectives: "resource", type and amount of materials to be redistributed; "accessibility", preferred distance and type of transportation used; "land use", land use, price, and building types; and "socio-economic", proximity to certain types of companies or individuals.

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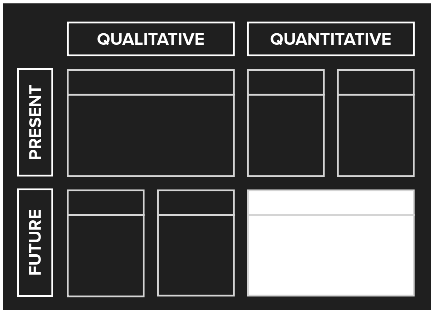

Chapter 7 uses quantitative methods and is future oriented. In the chapter, the optimal scale and locations of circular timber hubs are identified for Amsterdam and its surrounding region. The optimal scale and locations are defined as the combination of hub locations that are collectively the most cost effective, minimizing costs and maximizing emissions reductions through timber reuse. Spatial simulated annealing, a spatial optimization method, is used to balance the trade-off between small and large scale hubs - small scale hubs have lower transportation emissions, while large scale hubs allow for better supply and demand matching for waste timber. Building on the results of chapter 6, chapter 7 specifies methods and performs spatial analysis in a future oriented manner; predicting the potential impact of changing the scales and locations of closing material loops.

Finally, chapter 8 provides an overall conclusion for the dissertation by identifying five tensions for determining locations and scales for closing material loops, due to diverse and sometimes misaligned spatial perspectives. The first three tensions are conceptual, addressing contrasting perspectives for defining closing material loops - as urban manufacturing or urban mining; for their locations - as clusters or hubs; and for the factors that affect locations and scales - as spaces, people, or materials. The final two tensions are methodological, addressing contrasting approaches to time - looking at the present or the future; and to methods - quantitative or qualitative.

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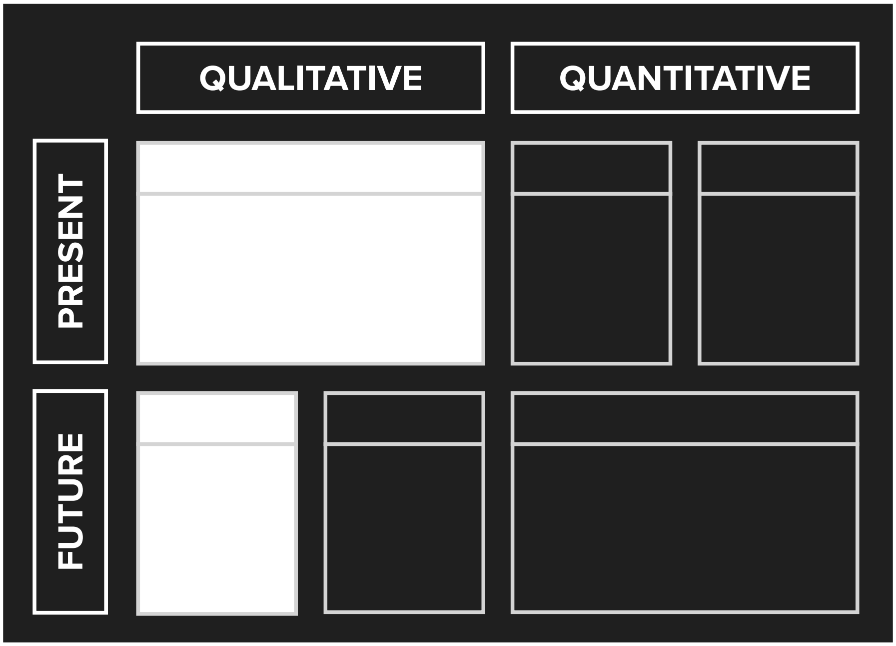
QUALITATIVE
QUANTITATIVE
PRESENT
FUTURE

3 Conceptualizing locations and scales in a circular economy

Based on the publication:
The role of urban manufacturing for a circular economy in cities
Tanya Tsui, David Peck, Bob Geldermans, and Arjan van Timmeren
Published in Sustainability (2021). 13, 23. https://doi.org/10.3390/su13010023

ABSTRACT In recent years, implementing a circular economy in cities (or “circular cities”) has been proposed by policy makers as a potential solution for achieving sustainability. One strategy for circular cities is to re-introduce manufacturing into urban areas (or “urban manufacturing”), allowing resource flows to be localized at the city scale. However, the extent to which urban manufacturing contributes to circular cities is unclear in existing literature. The purpose of this paper is therefore twofold: to understand whether urban manufacturing could contribute to the circular economy, and to understand the drivers and barriers to circular urban manufacturing. By reviewing existing literature and interviewing experts, we identified the caveats for the contribution of urban manufacturing to circular cities, as well as the spatial, social, and material-related drivers and barriers for circular urban manufacturing.

KEYWORDS circular economy, circular cities, urban manufacturing, drivers, barriers

3.1 Introduction

Cities have a large environmental impact - they consume 60-80% of natural resources globally, produce 50% of global waste, and 75% of greenhouse gas emissions (Camaren & Swilling, 2012). Reducing emissions and waste will be a major challenge for cities, and in recent years, transitioning to a circular economy has been proposed by policy makers as a potential solution.

While there is no common definition for the circular economy, it is generally understood as a closed-loop system that employs circular processes such as reuse, refurbishing, remanufacturing, and recycling to convert waste into resources. (Kirchherr, Reike, & Hekkert, 2017). To implement a circular economy at a city level, one proposed approach is to encourage local manufacturing in cities, minimizing the importation of raw materials and reliance on global supply chains (Fratini, Georg, & Jørgensen, 2019).

At the same time, a similar topic, "urban manufacturing", is being studied outside the field of circular economy, by scholars from urban planning, local economic policy, and manufacturing studies. These researchers explore the potential of re-introducing manufacturing into urban areas, by leveraging the availability of affordable, digital, and distributed production technology. (Cities of Making, 2020; Diez, 2018; Hirshberg, Dougherty, & Kadanoff, 2016; Rappaport, 2017; Wolf-Powers et al., 2017).

Although research on circular cities and urban manufacturing both study the localization of manufacturing in cities, exchange between the two fields is limited. Circular cities literature focuses on localizing material flows, but neglects the drivers and barriers for implementing urban manufacturing in cities. Urban manufacturing literature identifies drivers and barriers, but has a limited understanding on the environmental impact of urban manufacturing processes.

In order to fully articulate the potential and constraints of circular cities, insights from both circular city and urban manufacturing experts can be considered. This chapter therefore aims to answer the following two research questions:

1. **Does urban manufacturing contribute to a circular economy in cities, and if so, how?**
2. **What are the drivers and barriers to circular urban manufacturing?**

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By reviewing existing literature and interviewing experts on urban manufacturing and circular economy, we found that, while urban manufacturing contributes to a circular economy in cities, these claims come with a number of caveats, including the lack of empirical evidence, the relative insignificance of transportation emissions in the production process, and the reliance on global supply chains. With these caveats in mind, this chapter then gives a definition of “circular urban manufacturing”, and summarizes and categorizes its common drivers and barriers.

3.2 Theoretical background

3.2.1 Circular economy in cities

3.2.1.1 Circular economy and sustainability

Before introducing the theoretical background on circular economy in cities, a clarification on the relationship between the concepts of “circular economy” and “sustainability” is needed. While there appears to be connections between the two concepts, the similarities, differences, and relationships between the two remain ambiguous.

The most commonly accepted definition of sustainability is provided by the Brundtland Commission, stated as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (Brundtland Commission, 1987) Circular economy, on the other hand, can be defined as “a closed-loop system that employs circular processes such as reuse, refurbishing, remanufacturing, and recycling to convert waste into resources” (Kirchherr et al., 2017). Its most important theoretical influences include cradle-to-cradle (Braungart & McDonough, 2002), looped and performance economy (Stahel, 2008), and industrial ecology (Jelinski, Graedel, Laudise, McCall, & Patel, 1992).

The difference between the concepts of sustainability and circular economy are two-fold. Firstly, the two concepts differ in terms of scope. On one hand, sustainability is focused on the so-called “triple bottom line” (Elkington, 1997), and the three pillars of sustainability: people, profit, and planet. Literature on sustainability tends to focus on the “planet” pillar, measuring the environmental impact of activities using tools such as Life Cycle Assessments (LCA) and Material Flow Analysis (MFA). On the other hand, circular economy seems to have a stronger focus on the “profit” pillar, with literature dominated by a business-focused narrative aiming at profit-generating solutions, often in the form of business models. As a result, some authors argue that other dimensions, especially the social one, is not well integrated into the circular literature. (Murray, Skene, & Haynes, 2017; Prendeville, Cherim, & Bocken, 2018)

Secondly, the two concepts differ in terms of aims: while the main aim of a circular economy is a “closed loop” minimizing the use of primary raw materials and waste in a production system; sustainability addresses a multitude of issues such as greenhouse gas (GHG) emissions, land use, biodiversity loss, or toxicity, which may be prioritized differently according to the interest of researchers.

In a systematic literature review, Geissdoefer et al. (2017) categorized the relationship between CE and sustainability into three main types: ‘conditional’, ‘beneficial’, and ‘trade-off’. Some authors propose a ‘conditional’ relationship, stating that a circular economy is an essential condition or even the main solution for a sustainable system (Nancy M. P. Bocken, de Pauw, Bakker, & van der Grinten, 2016; Lieder & Rashid, 2016). Other authors propose a ‘beneficial’ relationship, stating that circular economy is one of several solutions for fostering a sustainable system (J. Allwood, Cullen, Carruth, & Cooper, 2012; N. M.P. Bocken, Short, Rana, & Evans, 2014). Finally, some authors also highlight a ‘trade-off’ relationship between circular economy and sustainability, describing, for example, the potential for circular systems to worsen the emission of greenhouse gases and accelerate global warming (J. M. Allwood, 2014).

This research takes the perspective of a circular economy having a ‘beneficial’ relationship with sustainability, meaning it is one of several potential solutions for fostering a sustainable system. For this research, a circular economy is therefore not a system that closes resource loops for its own sake. Instead, the goal of circular resource flows is to achieve sustainability. Additionally, this research aims to challenge the dominant view in existing circular literature, looking beyond products and business models to understand a circular economy implemented at the city scale, with a focus on techno cycle strategies such as reuse, refurbish, remanufacture, and recycle.

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3.2.1.2 Why circular cities?

There are compelling arguments in literature for the potential of cities to be major drivers of the circular economy. The density and diversity of stakeholders in cities aids collaborations in closing, connecting, and continuing resource loops, and allows for the creation of various agents, organisations, and networks, which is increasingly important in the transition to a circular society (Loorbach & Shiroyama, 2016). Waste collected at the city scale is at a large enough quantity to justify harnessing through urban mining (Li, 2015).The topic of “circular cities” has emerged recently, including research reports on circular cities published by municipalities (Circle Economy, 2016; Circularity City, 2018; Gemeente Amsterdam, 2020), and academic papers (Gravagnuolo, Angrisano, & Girard, 2019; Remøy, Wandl, Ceric, & Van Timmeren, 2019; Williams, 2019a).

3.2.1.3 Connecting circular cities with urban manufacturing

Literature on circular cities can be separated into three main perspectives: Space (urban planning), People (urban governance), and Flows (urban metabolism). The spatial (or urban planning) perspective refers to investigation as to how urban planning and zoning strategies affect circular activity in cities (Ferm & Jones, 2016; Williams, 2019b). The people (or urban governance) perspective investigates how municipalities and policy makers implement circular strategies at the city level (Fratini et al., 2019; Prendeville et al., 2018; Williams, 2019a). The flows (or urban metabolism) perspective investigates the flows of materials and waste in a city, and how resource flows can be recirculated at the city level (Mulrow, Derrible, Ashton, & Chopra, 2017; Rosado & Kalmykova, 2019).

One strategy in circular cities literature is the localization of resource flows - to minimize the importation of raw materials and production of waste (Cappellaro et al., 2019; Fratini et al., 2019; Joshi, Seay, & Banadda, 2019; Kampelmann, 2020; Oliveira, França, & Rangel, 2018), by employing various circular activities. Strategies for developing circular economy in cities divides into two broad categories:

- Increasing production of products using locally grown raw materials (Risku-Norja, Hietala, Virtanen, Ketomäki, & Helenius, 2008; Säumel, Reddy, & Wachtel, 2019)
- Increasing production or use of products using local secondary raw materials, which involves circular processes such as, refurbishing, remanufacturing and recycling. (Boeri, Gaspari, Gianfrate, Longo, & Boulanger, 2019; Campbell-Johnston, Cate, Elfering-Petrovic, & Gupta, 2019)

The majority (and most cited) articles on the localization of resource flows at the city level propose the implementation of eco-industrial parks. (Chang & Sheppard, 2013; de Jong, Wang, & Yu, 2013; Geng, Tsuyoshi, & Chen, 2010; Vergragt, Dendler, de Jong, & Matus, 2016). However, literature is recently beginning to explore how circular economy can be implemented on the city as a whole, looking beyond eco-industrial parks and integrating industrial activity into urban areas. Rosado & Kalmykova (2019) developed a method to facilitate industrial symbiosis in the food industry in the municipality of Gothenburg, Sweden (Rosado & Kalmykova, 2019). Mulrow et al. (2017) explores industrial symbiosis opportunities at the scale of a single facility housing multiple firms, as an alternative to existing strategies for industrial parks (Mulrow et al., 2017).

However, while there is interest in the introduction of circular industrial activity into urban areas within circular cities literature, there is limited investigation into the drivers and barriers of implementing this. On the other hand, literature on “urban manufacturing”, which investigates the (re-)introduction of industrial activity into urban areas, focuses on principles that could potentially fit into a circular economy at the city level.

3.2.2 Urban manufacturing

Research on urban manufacturing is motivated by a renewed interest of relocating manufacturing to urban areas. Technological developments allow manufacturing processes to be smaller, quieter, less polluting, and distributed; making it easier for manufacturers to justify their presence in cities (Doussard, Schrock, Wolf-Powers, Eisenburger, & Marotta, 2018; Hatuka, Ben-Joseph, & Peterson, 2017; Unterfrauner, Voigt, Schrammel, & Menichinelli, 2017). The increased availability of cheap digital fabrication tools such as Computerized Numerical Control (CNC) routers, laser cutters, and 3D printers (also known as ‘additive manufacturing’), as well as the increased presence of open workshops (such as fab-labs and makerspaces), has given more individuals and small businesses the opportunity to engage in urban manufacturing activity (Diez, 2018; Hirshberg et al., 2016). Urban manufacturing creates opportunities in local economic development (Wolf-Powers et al., 2017), and some manufacturing businesses are also motivated to move back to urban areas to be closer to customers, business partners, consultancy services, and suppliers (Doussard et al., 2018; Sassen, 2009).

Urban manufacturing is studied under diverse disciplines and perspectives, and thus falls under a variety of different names. Under the term “industrial urbanism”, urban planners study how urban form affects the development of industry in cities, and how new technological developments creates the potential for new forms of industry in urban areas (Hatuka et al., 2017; Rappaport, 2017). Under the term “urban manufacturing”, policy researchers examine the drivers and barriers for urban manufacturing companies, as well as their potential for local economic development (Doussard et al., 2018; Schrock & Wolf-Powers, 2019; Wolf-Powers et al., 2017). Under the term “distributed manufacturing” and “re-distributed manufacturing”, designers study the priorities and capabilities of maker communities, as well as their potential for contributing to sustainability (Diez, 2012; Kohtala, 2015; Millard, Sorivelle, Deljanin, Unterfrauner, & Voigt, 2018; Unterfrauner & Voigt, 2017).

Some researchers (Diez, 2011; Hirshberg et al., 2016) go one step further, exploring how makerspaces can proliferate throughout a city, allowing for more independence from global supply chains. This research is connected to initiatives that aid cities in harnessing the potential of the maker movement: The Fab City initiative[2], which is a global initiative for locally productive cities that originated in Barcelona; and Maker City[3], which is an initiative that originated from the US, in response to the increasing popularity of the maker movement.

The definition of urban manufacturing varies across literature, and there is limited consensus on which types of production can be categorized as urban manufacturing. The main discrepancies of the definitions are due to scale of production. While some articles take a broader view of urban manufacturing and include craftsmen engaged in batch production (Wolf-Powers et al., 2017), other articles on the topic only focus on manufacturers that operate at an industrial scale (Cities of Making, 2020).

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[2] https://fab.city/

[3] https://makercity.com/

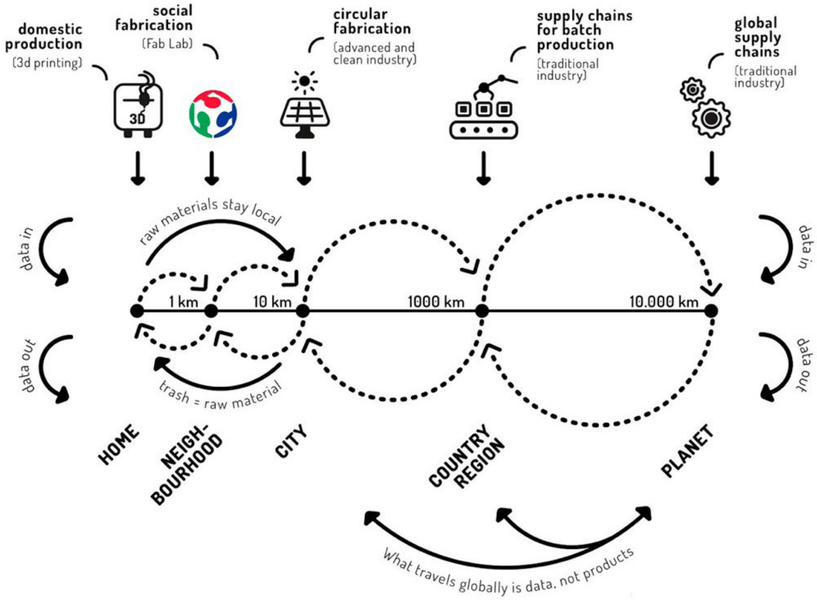

FIG. 3.1 A multi-scalar and complimentary fabrication ecosystem. Different types of manufacturing are included in this diagram, roughly categorized by the scale of material flows, from small (home, neighborhood) to large (country, planet) scale. (Diez, 2011)

Fab City[4], a global initiative promoting locally productive cities, provides a clear framework for different types of urban manufacturing, roughly categorized according to their scale of production (see Figure 3.1 above):

- **Personal fabricators**
  hobbyists (sometimes referred to as “makers”) making products for personal use
- **Maker spaces**[5]
  workshops where makers share fabrication space, equipment, and ideas.
- **Mini-factories**[6]
  small to medium sized manufacturing companies that have less than ~20 employees
- **Traditional urban industry**
  large-scale manufacturers that have chosen to stay in the city instead of offshoring production.

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[4] https://fab.city/

[5] examples of makerspaces / fab labs can be found on: http://fablab.org/, https://artdesignxchange.com/

[6] examples of mini factories can be found on: https://make.works/, https://madeinnyc.org/, https://www.urbanmfg.org/

This chapter will focus on urban manufacturing activity at the scale of makerspaces and mini-factories, and for consistency, all manufacturing in cities will be referred to as “urban manufacturing”.

3.2.2.1 Urban manufacturing and circular economy in cities

While there is existing research on the effects of urban manufacturing on local economic development, the contribution of urban manufacturing to the circular economy requires further study. In the existing literature, the potential environmental benefits of urban manufacturing are based on the following the claims: that local supply chains can reduce transportation emissions (Hennelly et al., 2019; Kohtala & Sampsa, 2015; Prendeville, Hartung, Purvis, Brass, & Hall, 2016), and that urban manufacturers can utilize local waste flows as a resource (Gravagnuolo et al., 2019; Prendeville et al., 2018; M. Russell, Gianoli, & Grafakos, 2019; Williams, 2019b). However, there are caveats to these claims. While many articles have claimed that urban manufacturing contributes to a circular economy, most of these claims are not supported by empirical evidence (Kohtala, 2015). This article therefore aims to provide a deeper understanding of whether urban manufacturing contributes to a circular economy at the city level, as well as the drivers and barriers to scaling up urban manufacturers to increase their positive impact.

3.3 Materials and Methods

The aim of this research is to establish the extent to which urban manufacturing contributes to developing a circular economy in cities. This chapter therefore will attempt to answer two research questions:

1. **Does urban manufacturing contribute to a circular economy in cities, and if so, how?**
2. **What are the drivers and barriers to circular urban manufacturing?**

The research questions are answered using three sources of information: a literature review of Life Cycle Assessments (LCAs) of urban manufacturing processes, semi-structured interviews of experts within the fields of circular economy and urban manufacturing, and a literature review of drivers and barriers in both circular cities and urban manufacturing.

3.3.1 Literature review on Life Cycle Assessments (LCAs) of urban manufacturing

It was decided that a literature review of LCAs was appropriate for this research because LCA is a widely accepted and standardized methodology for assessing environmental impacts of products, processes, and services. The rigorous nature of LCAs allows for a relatively reliable comparison between different production scenarios, such as manufacturing using local versus global supply chains, or manufacturing for a local versus global consumer base.

For the literature review of life cycle assessments (LCAs) of urban manufacturing processes, the Scopus search engine was used to search for peer-reviewed articles that conducted a life cycle analysis on the environmental impacts of urban manufacturing. The search terms used were: TITLE-ABS-KEY (“makerspace” OR “urban industry” OR “local industry” OR “distributed industry” OR “urban manufacturing” OR “distributed manufacturing” OR “local manufacturing” OR “urban production” OR “local production” OR “distributed production” AND “LCA” OR “environmental impact” OR “carbon emissions”).

The resulting 63 document results were further narrowed down to 9 articles, which examined the environmental performance of different types of food and consumer products. For a full list of literature reviewed, please refer to the supplementary materials section.

The articles were chosen based on the following criteria: each article conducted a life-cycle assessment that provided empirical evidence for the total GHG emissions during the production and transportation process; and made a comparison between the environmental impact of urban (or distributed) manufacturing and traditional centralized manufacturing.

3.3.2 Semi-structured interviews with experts in circular economy and urban manufacturing

Semi-structured interviews was selected as a method for this research because the conversational nature of semi-structured interviews allows for a deeper understanding of the topics explored, giving interviewees an opportunity to elaborate on relevant case studies and speculative ideas that cannot be found in literature. The interviewees, who were either practitioners or researched closely with practitioners, provided additional insights from the perspective of urban manufacturers, which is essential to understanding drivers and barriers.

For the interviews of experts within the fields of circular economy and urban manufacturing, eight interviewees were chosen based on their expertise in urban manufacturing and circular cities, as well as recommendations from previous interviewees. The interviews were semi-structured, and conducted online.

The interview questions were as follows:

1. What is your definition of circular cities?
2. What is your definition of urban manufacturing?
3. Could urban manufacturing be a driver for the circular economy?
4. Could circular economy be a driver to urban manufacturing?
5. Could urban manufacturing and circular economy be a barrier for each other?
6. Why should/shouldn't manufacturing be situated in cities?
7. Where in cities should they be situated, and why?
8. What kinds of manufacturing is / is not suitable for cities?
9. In what condition should products be produced locally?
10. How do you see the future of manufacturing in cities?

TABLE 3.1 List of interviewees

Name	Role	Date
Interviewee A	Academic on urban planning, urban planning history, urban manufacturing	07/02/2020
Interviewee B	Academic on urban economic planning, urban manufacturing, the maker movement	12/02/2020
Interviewee C	Academic on circular economy, energy	03/04/2020
Interviewee D	Academic and practitioner on urban manufacturing, urbanism, the maker movement, fab.city co-founder	09/04/2020
Interviewee E	Practitioner on urban manufacturing network building	10/04/2020
Interviewee F	Academic on urban manufacturing, urban planning	21/04/2020
Interviewee G	Academic on circular economy, policy and business models for recycling and reuse	26/05/2020
Interviewee H	Practitioner on circular economy, building product reuse	03/06/2020

With insights from the literature review and expert interviews, it is then possible to establish whether and how urban manufacturing contributes to a circular economy at the city level. Urban manufacturing that contributes to a circular economy will be defined, within this chapter, as “circular urban manufacturing”. This definition allows us to answer the second research question, defining the drivers and barriers for circular urban manufacturing.

3.3.3 Literature review of drivers and barriers to circular urban manufacturing

The second research question is answered with a literature review of drivers and barriers identified in both circular city and urban manufacturing literature. Drivers and barriers that apply to circular urban manufacturing are identified and categorized into three perspectives: space, people, and flows.

These three perspectives were chosen because the factors that affect the presence of manufacturing in urban areas are multi-faceted. Not only is the presence of urban manufacturing dependent on the availability of materials and technology (flows), it is also dependent on spatial issues (such as the availability of industrial land), and people-related issues (such as the presence of a support ecosystem). Instead of conducting an in-depth exploration onto one perspective, this chapter aims to give readers a broad overview of issues connected to circular urban manufacturing. The three perspectives take reference from the Ecopolis framework of Urbanist Sybrand Tjallingii, where he highlights a threefold strategy for ecologically sound development, focusing on 'sites', 'participants', and 'flows' (Tjallingii, 1995).

This chapter changes the wording of the framework, to 'space', 'people', and 'flows'. 'Space' refers to issues related to land-use, land prices, and proximity of stakeholders. 'People' refers to issues related to management, money, networking, and education. 'Flows' refers to issues related to material flows, supply chains, and logistics.

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3.4 Results

3.4.1 Does urban manufacturing contribute to a circular economy at the city level?

In order to understand whether urban manufacturing contributes to a circular economy at the city level, a literature review of LCAs of urban manufacturing was conducted. Typically, the LCA method takes into account a variety of different environmental impact categories, such as greenhouse gas (GHG) emissions, land use, toxicity, acidification, eutrophication, ozone depletion, and various other indicators. This research, however, focuses on GHG emissions as an indicator of environmental impact, because reducing GHG emissions is a major strategy for mitigating the environmental damage of global warming and climate change (IPCC, 2018). Moreover, GHG emissions is an indicator that is commonly used across most LCA studies, allowing for a more reliable comparison between different findings.

3.4.1.1 Empirical evidence for environmental impact of urban manufacturing

In articles that conducted an LCA on urban manufacturing processes, authors found that, while urban manufacturing contributes to reducing GHG emissions, this claim comes with a number of caveats and conditions.

Using LCAs, a number of authors provided empirical evidence for the positive environmental impact of urban manufacturing. Authors found that shortening transportation distances reduces GHG emissions by 0.8 - 2.6%, although improving other parts of the production process had a more significant impact. Benis & Ferrão (2017) found that eliminating losses and wastage during the production processes reduced emissions by 8%, while Russell & Allwood (2008) found that urban manufacturing with recycled materials reduces emissions by 9.5% (Benis & Ferrão, 2017; S. N. N. Russell & Allwood, 2008). This is because, for most consumer products, the largest source of emissions comes from production of raw materials, not transportation.

Other authors also found that urban manufacturing reduced GHG emissions, not due to shorter transportation distances, but due to other aspects of the urban manufacturing process. Hall et al. (2014) found that localizing the production of food had a positive environmental impact, because local farmers were more environmentally conscious and used better fertilizers. M. Kreiger & Pearce (2013) found that distributed manufacturing of consumer products with 3D printers can reduce emissions, because they are more energy efficient, and 3D printed products use less materials (Hall et al., 2014; Kreiger & Pearce, 2013).

However, authors found that urban manufacturing also creates changes in the production process that lead to a negative environmental impact. A number of authors found that, for some types of food, decentralized manufacturing can be less environmentally friendly because smaller manufacturers cannot take advantage of the efficiencies of economies of (Almena, Lopez-Quiroga, Fryer, & Bakalis, 2019; Hall et al., 2014). Localizing manufacturing may also lead to a negative environmental impact because of the local context. For example, the local electricity grid may use less renewable sources (S. N. N. Russell & Allwood, 2008), or local climate conditions lead to less efficient production of crops (Kreidenweis, Lautenbach, & Koellner, 2016).

3.4.1.2 Caveats to the circularity of urban manufacturing found in literature and expert interviews

From literature and expert interviews, it was found that there are a number of caveats to the claims that urban manufacturing contributes to a circular economy. While many articles have claimed that urban manufacturing contributes to a circular economy, most of these claims are based merely on potential benefits, and are not backed-up by empirical evidence (Kohtala, 2015). Moreover, not all types of urban manufacturing contribute to a circular economy in cities.

Not all urban manufacturers source from local supply chains. While some urban manufacturers may start off their business by sourcing local materials from nearby suppliers, it is difficult to stay local, especially when production starts scaling up. For many urban manufacturers, relying on offshore supply chains or moving manufacturing completely offshore is the only way to scale up production. In many cases, local manufacturing networks simply cannot compete with global offshore networks when it comes to price, efficiency, and knowledge (Doussard et al., 2018; Schrock & Wolf-Powers, 2019; Srai et al., 2016).

Not all urban manufacturers aim to serve a local consumer base. These manufacturing businesses (referred to as “global innovators” by (Wolf-Powers et al., 2017)) often manufacture high-tech products, and are located in cities in order to access knowledge networks with highly skilled professionals, such as designers, engineers, academics, or consultants. The products that these manufacturers produce, such as specialized medical or aerospace equipment, have a consumer base that far exceeds the boundaries of the city that the manufacturer is located in (Wolf-Powers et al., 2017). An urban manufacturing expert states, *“of course there are manufacturers that just produce for the local population, but for most companies to compete in the marketplace, they can’t limit where they sell. And with global commerce and free trade, you can sell anywhere (in the world).”* (Interviewee A)

The issue of limiting supply to a single city also applies to circular product life extension processes such as reuse and recycling. Expert interviewees stated the impracticality of recycling certain types of materials at the city-scale.

- “In Belgium, there’s just a couple of metal treatment plants. So anytime a building is being totally renovated or rebuilt, all that steel that comes out gets taken to Antwerp or Ghent to be recycled.” (Interviewee F)
- “It’s an issue of the product and the scale. If you have, let’s say, small lithium batteries, you need quite a lot of them to make it worth setting up a recycling plant. You could imagine that you only need one plant for the whole of the UK.” (Interviewee C)
- “Large recycling processors want to have tons (of waste) coming in monthly, because they’re looking for a certain percentage of returns for their investors. I don’t think it’s economically viable for them to operate within a city.” (Interviewee G)

Even if urban manufacturers had a positive environmental impact, their contribution to the overall environmental impact of a city is insignificant, as cities are still reliant on global centralized manufacturers. Urban manufacturers often operate at a smaller scale compared to centralized global manufacturers due to spatial and financial constraints, or simply because they don’t desire to scale up (Wolf-Powers et al., 2017).

From the expert interviews and the literature, one of the main paradoxes in urban manufacturing literature is this: if urban manufacturers want to stay local, they must stay small, reducing their potential impact on the city. If they scale up and try to grow their business, their positive impact may increase, but they often leave the city completely.

After examining the caveats on the sustainability of urban manufacturing, it can be concluded that urban manufacturing would only contribute to the circular economy under a number of conditions. Therefore, for this chapter, “circular urban manufacturing” can be defined as urban manufacturing processes where:

- The business sources from local supply chains, and produces for a local consumer base.
- Transportation emissions of the product being manufactured contributes to a significant percentage of the total environmental impact of the product. (For example, products produced from secondary raw materials will have much lower emissions associated with material extraction and processing.)
- Local waste or secondary raw materials is used as a resource
- There is a possibility of scaling up without moving out of the city.

3.4.2 Drivers and barriers to circular urban manufacturing

Through a literature review and interviews with experts, the drivers and barriers to circular urban manufacturing can be derived. Since there is limited literature and experts that examine the overlap between the two topics, the drivers and barriers for circular cities and urban manufacturing were extracted separately. Then, drivers and barriers that were relevant to “circular urban manufacturing” (as defined in the previous section) were selected and summarized in the following section.

3.4.2.1 Drivers

The drivers for circular urban manufacturing come in two categories - “push” and “pull” factors. “Push” factors refer to the potential benefits that could occur if circular urban manufacturing could happen at a larger scale. “Pull” factors refer to external conditions from the surrounding context that create a fertile environment for circular urban manufacturing.

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3.4.2.2 Push factors – potential benefits of circular urban manufacturing

In terms of push factors related to urban space, digitization of manufacturing has allowed production processes to operate at a smaller scale, justifying the presence manufacturing in urban areas, despite higher rental costs (R. Freeman, McMahon, & Godfrey, 2016; Srai et al., 2016). For urban planners, re-introducing urban manufacturing has the added benefit of place-making, “connecting the means of production and tapping into the city’s creative and constructive spirit” (Hatuka et al., 2017).

In terms of societal push factors, advocates for urban manufacturing are motivated by the potential of reshoring manufacturing (Srai et al., 2016), which could promote local economic development and create local working class jobs (Hatuka et al., 2017; Wolf-Powers et al., 2017). Increasing urban manufacturing can also lead to more independence from global supply chains. Cities with less urban manufacturers are arguably less resilient to disruptions in global supply chains (Rachel Freeman, McMahon, & Godfrey, 2017). Increasing local production could also allow producers to avoid negative externalities, which are often hidden in the complexity of global supply chains (Interviewee D).

Designers and manufacturers, on the other hand, are motivated by the fact that distributed manufacturing technologies create the opportunity for open, accessible, manufacturing and fast prototyping. Smaller and cheaper digital fabrication technologies make them more accessible, lowering the threshold of capital required to start a manufacturing business (Interviewee B). Organizational nimbleness and reduced prototyping costs allow designers and manufacturers to get their work into the public domain without too much upfront investment, allowing for a shorter and faster product development cycle. (Doussard et al., 2018; Prendeville et al., 2016; Srai et al., 2016; Unterfrauner et al., 2017)

In terms of flow related factors, urban manufacturing has the potential to contribute to a circular economy – shorter supply chains mean lower transportation emissions (Kohtala, 2015; Millard et al., 2018; Prendeville et al., 2016; Srai et al., 2016), and increased local manufacturing capacity gives a greater potential for turning local secondary or residual materials into local resources (Gravagnuolo et al., 2019; Hennelly et al., 2019; Srai et al., 2016; Williams, 2019a). Moreover, the maker movement has a thriving repair, recycle, and upcycle culture, where, for example, additive technologies can facilitate the reparability of products (Prendeville et al., 2016; Unterfrauner et al., 2017).

3.4.2.3 Pull factors – existing environmental drivers

In terms of spatial factors, authors found that the presence of urban manufacturing depends on the availability of affordable industrial land and manufacturing spaces. Municipalities' protective industrial zoning strategies have a positive effect on the presence of both circular and urban manufacturing activity. This is illustrated in the case study of urban manufacturing activity in Portland, USA (Schrock & Wolf-Powers, 2019), as well as in circular cities literature (Campbell-Johnston et al., 2019; Prendeville et al., 2018). Protective industrial zoning was mentioned during interviews as well, "if cities actually got serious about enforcing industrial zoning, and making sure that there were affordable production spaces, then I think you'd see a lot more small makers able to expand." (Interviewee B)

Protective industrial zoning policies depend on the local government's ownership and control of land, which prevents private developers from converting industrial land into more profitable residential or commercial land (Campbell-Johnston et al., 2019; Leigh & Hoelzel, 2012). This was also pointed out by an urban manufacturing expert, "in hot market cities, cities are feeling tons of pressure to convert industrial land to housing or to other commercial uses like hospitality. There are advocates in those cities fighting to retain that industrial land so that those (manufacturing) jobs can stay there." (Interviewee E) Additionally, interviewees point out that smaller declining towns with cheap real estate could have an advantage in revitalizing urban manufacturing (Interviewees B, G, H)

Space providers for makers, such as makerspaces and mission driven real estate developers, also increase urban manufacturing activity (Hennelly et al., 2019). For example, New York's Greenpoint Manufacturing and Design Center and Brooklyn Navy Yard, Tillamook Station in Portland, and the Industrial Council of Near West Chicago are operated by mission-driven industrial landlords that take a double bottom-line approach to their rental properties (Wolf-Powers et al., 2017).

In terms of people-related pull factors, disturbances in global supply chains have the potential to increase urban manufacturing activity. An interviewee uses the example of the Covid-19 global pandemic, "A lot of cities are missing capacities to deal with (the pandemic), and to find materials for personal protective equipment. Cities like London and New York, that have kicked out their manufacturers, are now really depending on Fab Labs to produce these materials." (Interviewee F)

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Individual urban manufacturers locate in urban areas in order to be closer to existing customers and support networks. In order to compensate for higher rental costs, urban manufacturers target their products towards specific consumer markets that are willing to pay a higher price of urban manufactured goods. Customers of urban manufacturers include:

- wealthy, environmentally-conscious customers who are interested in locally-produced, design-driven, or customized products (Hatuka et al., 2017; Sassen, 2009; Srai et al., 2016); (Interviewees B, C)
- design or technology driven companies, in sectors such as architecture, theatre, aerospace, that require customized manufacturing services (Sassen, 2009; Schrock & Wolf-Powers, 2019) (Interview Hill, Rappaport, Stanton)
- niche markets, such as custom-made shoes, high-end bicycle messenger bags, or custom made fire-fighter jackets (Doussard et al., 2018; Unterfrauner et al., 2017); (Interviewees A, B)

Experts have found that the existence of support networks aimed towards urban manufacturers contributes significantly to a thriving urban manufacturing sector in a city. Support networks are important to urban manufacturers because these businesses often operate at a smaller scale and at a higher risk. Stakeholders in support networks include:

- large scale traditional manufacturers that collaborate with makers in prototyping products or integrate makers into their production chain as sub-contractors (Hatuka et al., 2017; Hennelly et al., 2019; Millard et al., 2018; Schrock & Wolf-Powers, 2019); (Interviewees C, E)
- local production networks, which include local supply-chains of small-scale manufacturers, makerspaces which provide access to space and fabrication technology, as well as potential business partners and contractors (Sassen, 2009; Schrock & Wolf-Powers, 2019); (Interviewee F)
- skilled workers and professionals (Burggräf, Dannapfel, Uelpenich, & Kasalo, 2019; Schrock & Wolf-Powers, 2019; Wolf-Powers et al., 2017); (Interviewee A, C)
- experts, consultants, and universities (Hatuka et al., 2017); (Interviewee A)
- marketing or business support, such as branding organizations (Wolf-Powers et al., 2017)

In terms of flow-related pull factors, circular urban manufacturing is driven by the existing availability of municipal and industrial waste and secondary materials. There is a substantial accumulation of municipal waste in cities, as well as construction and demolition waste from buildings and infrastructure that have been either demolished or undergoing refurbishment. Moreover, new regulations such as China's Green Fence Operations in 2013 prevents large quantities of waste from being exported to developing countries. In the long term, this gives an opportunity for cities to recycle waste locally (Williams, 2019a). An expert interviewee referenced municipality-led efforts to *"encourage manufacturing companies to locate in the city to focus on municipal trash"* (Interviewee G). Proximity to the end user also provides opportunities for recapturing valuable materials from products at their end of life (Srai et al., 2016).

Industrial waste, on the other hand, is usually higher in quality and quantity, which gives more opportunity for circular processes to happen at an industrial scale. An expert interviewee states that, *"from our research in London, we found that there is a huge amount of industrial waste, and it's relatively pure in the sense that it can be sorted relatively easily… there's a lot of capacity for the industrial sector manufacturers to be a lot more effective with their waste streams, so that's a real opportunity."* (Interviewee F).

Table 3.2 below summarizes the drivers for circular urban manufacturing, categorized into issues related to 'space', 'people', and 'flows'.

TABLE 3.2 Summary of drivers for circular urban manufacturing.

Space	People	Flows
Push factors		
– Manufacturing is cleaner, quieter, and smaller, allowing manufacturing to move back into the city – Potential for place-making	– Potential for reshoring manufacturing – Independence from global supply chain – Democratized manufacturing – Faster prototyping and product development	– Potential for turning local waste to a local resource – Potential lower transportation emissions – Repair, recycle, upcycle culture in the maker movement
Pull factors		
– cheap real estate in smaller declining towns – availability of industrial land – space providing stakeholders for makers	– disturbances to the linear global supply chains – access to support networks – existing consumer market for circular urban manufacturing	– availability of waste (municipal waste, industrial waste, waste not worth shipping to other countries)

3.4.2.4 Barriers

A major spatial barrier for both circular and urban manufacturing activity is the lack of industrial land in cities, which limits the availability of affordable spaces for both circular infrastructure (such as spaces for storage, collection, and recycling of materials) (Williams, 2019b, 2019a) and manufacturing spaces (Doussard et al., 2018; Hennelly et al., 2019; Schrock & Wolf-Powers, 2019; Wolf-Powers et al., 2017). Researchers have observed that municipalities are allowing the conversion of industrial land into commercial and residential land to take advantage of higher property tax revenues. A global political shift towards neoliberalism has also led to the privatization of government-owned land, reducing municipalities' abilities to protect industrial land (Williams, 2019a).

Even if urban manufacturers have non-polluting and quiet production processes, outdated land-use and zoning regulations prevent them from using non-industrial spaces (Hatuka et al., 2017). When discussing zoning regulations, an expert on urban manufacturing stated, *"many of these zoning regulations are outdated. The big question now is how to create what's called 'performance zoning', whereby we can judge whether the factory is suitable for its urban location on a case by case basis, rather than having a blanket regulation."* (Interviewee A)

This raises the connection between urban planning and the development of urban manufacturing. Many European cities are converting their existing industrial areas into mixed living and working environments, with the hopes that some specific industries could continue to thrive. These efforts are not always successful - increased land values, nuisance complaints, and negative perceptions can drive manufacturers away from regenerated industrial districts. Thus, the scaling up of urban manufacturing depends heavily on the city development context.

Moreover, while cities may have land suitable for manufacturers, these areas can remain abandoned and under-used. Authors have studied this phenomenon under the term 'wastescapes', which includes areas in cities such as abandoned territories, underused areas, former industrial areas, and operational landscape and infrastructure for waste management. While wastescapes undoubtedly create negative impacts on surrounding areas, they also provide the possibility of creating a positive impact through regeneration. For example, regenerating these 'wastescapes' can help support circular concepts by incorporating land-use functions and facilities that help to close resource loops (Amenta & van Timmeren, 2018). Allowing manufacturers to locate in wastescapes could partially increase the availability of affordable industrial land for urban manufacturers, as well as provide an opportunity to turn wastescapes into more productive and circular areas.

In terms of people related barriers, it was found that, although urban manufacturing may have social, economic, and environmental benefits, circular urban manufacturers often operate at a small scale, and have a limited impact. Circular urban manufacturers are often limited to producing products in luxury or niche markets, as they cannot compete in terms of price, volumes, and delivery schedules with globally produced products (Srai et al., 2016; Wolf-Powers et al., 2017).

For urban manufacturers, higher sales prices of niche or luxury products compensates for higher rental costs (Doussard et al., 2018). Circular manufacturers in the repair or reuse industry, on the other hand, are limited to collecting and reusing high value waste, to take advantage of higher resale values. Expert interviewees cited examples for the re-use industry in construction materials: *"The only part of the industry that survived initially, were the people going for the high end material - the Tiffany chandeliers, the doorknobs, the architectural millwork."* (Interviewee H)

Although urban manufacturers could theoretically have a greater positive impact by scaling up, there are many significant barriers which prevent them from doing so. Urban manufacturers often lack the resources and knowledge required to scale up their business. In terms of access to resources, urban manufacturing firms lack access to capital and are not prioritized by investors. Without extra funding, firms find it difficult to invest in the technology or space required to scale up production. An expert on urban manufacturing states, *"There's a lot of venture capital running around looking for investment, but it has a bias towards immaterial things like software. Software or anything that has to do with tech is a magnet for angel investors and venture capital investors; whereas it's considered much more risky and kind of less 'sexy' to invest in a company that's making (physical) things."* (Interviewee B) This lack of access to capital links to the need for powerful 'launching customers', such as governments or traditional industrial companies that could integrate mechanisms into their purchasing guidelines and place more emphasis on the value of urban manufacturers nearby.

Due to their small scale, urban manufacturers have limited access to both local and global production networks. Unlike traditional manufacturing companies, urban manufacturers have limited connections, making opaque supply chains difficult to navigate. Sub-contractors may also require a 'minimum order' that exceeds the production capacity of smaller firms. (Doussard et al., 2018)

With limited capacity and personnel, urban manufacturing firms lack the knowledge required to scale up their business, including knowledge in production management, high quality manufacturing, as well as business skills such as marketing and accounting (Doussard et al., 2018). An expert interviewee also noted that *"there's not as much technical assistance available, or orientation to business available to people who are manufacturing entrepreneurs"* (Interviewee B).

When urban manufacturers do manage to scale up their business, there is no guarantee that their production will stay in the city. When the scale of production increases, more production space is needed, making an urban location even more expensive. Sourcing from offshore networks becomes a better option, because production capacity, knowledge, and cheap services are more available in other countries (Doussard et al., 2018; Schrock & Wolf-Powers, 2019; Wolf-Powers et al., 2017).

Even if they stay in the city and source locally, successful urban manufacturers often get acquired by multinational firms that swiftly decide to move production offshore to countries with a lower labour cost. An urban manufacturing expert recalls a particularly successful manufacturer in Portland, *"they were really scaling up and moved to a bigger space, and then all of a sudden we read that they had been acquired by a multinational and they were leaving the area."* (Interviewee B).

Table 3.3 below summarizes the barriers for circular urban manufacturing, categorized into issues related to 'space', 'people', and 'flows'.

TABLE 3.3 Summary of barriers for circular urban manufacturing.

Space	People	Flows
– scaling up = moving production away from urban areas or overseas – outdated land-use and zoning regulations – industrial land in cities is being replaced by commercial and residential land – lack of affordable space for circular urban manufacturing	– limited access to business-related services – lack of knowledge required to scale up business – limited access to larger production networks – limited to market for high-value or niche products	– scaling up production leads to sourcing from offshore networks – scaling up production leads to being acquired by multinational firms that move production offshore

3.5 Discussion

The purpose of this chapter was to identify the extent to which urban manufacturing could contribute to a circular economy in cities. Through reviewing existing literature and expert interviews, a number of caveats were revealed on the circularity of urban manufacturing. This section will identify and explain the significance of these caveats, as well as propose possible directions for further research.

3.5.1 Geographical scales of the circular economy

Our review of urban manufacturing LCAs has found that shortening transportation distances reduces GHG emissions by 0.8 - 2.6%, but improving other parts of the production process has a more significant impact. The relative insignificance of transportation emissions implies that reducing the geographical distance between suppliers, producers, and consumers may not significantly reduce the negative environmental impact of production processes.

This echoes existing literature in the field of industrial ecology investigating the geographical scales of resource flows: here, researchers have found that localizing resource flows is often not the most effective strategy for sustainability, and that there is no ‘ideal’ scale for resources to be (re)circulated (D. I. Lyons, 2007; D. Lyons, Rice, & Wachal, 2009; Park & Gupta, 2015; Velenturf & Jensen, 2016).

The implicit bias of circular cities literature towards local (as opposed to global) supply chains could be better understood (D. Lyons et al., 2009). Further research can be conducted on the conditions under which (re)circulating resources at a local scale is more preferable to a national or global scale. By understanding the conditions affecting the geographical scales of resource flows, we can identify what types of urban manufacturing could contribute to the circular economy, and under which conditions.

What was not discussed in this chapter is the environmental impact of urban manufacturing on its immediate surroundings, or ‘micro-impacts’. Although authors have made general statements on how new technology allows manufacturers to limit its nuisance on its neighbors nearby (Hatuka et al., 2017; Rappaport, 2017), there seems to be limited literature on the micro impacts of distributed manufacturing technology, such as the toxicity of 3D printer fumes (Kohtala, 2015), or health and safety impacts of having more delivery trucks in a neighborhood due to the presence of an urban manufacturer. If urban manufacturing will become more commonplace in the future, micro-impacts could potentially become a significant concern.

3.5.2 Locally embedded urban manufacturers

Literature on urban manufacturing seems to be partially motivated by the assumption that urban manufacturers are embedded ‘locally’ in the cities they are located in – that they make use of local suppliers, produce for a local consumer base, and contribute to local economic development – but we have found that this is not always the case.

There are two potential further research directions in response to this finding. Firstly, it would be beneficial to categorize urban manufacturers according to how ‘locally embedded’ they are in terms of material use – whether they utilize local, national, or global supply chains; and whether they sell to a local, national, or global consumer base. Wolf-Powers (2017) has made an excellent categorization of urban manufacturers in the US according to their potential for local economic development (Wolf-Powers et al., 2017). A similar categorization can be made from the perspective of local material flows.

Secondly, the environmental impact of different types of urban manufacturers could be empirically measured. This could establish whether environmental performance has any correlation with how ‘locally embedded’ urban manufacturers are.

3.5.3 Scale of production and environmental impact

Our findings indicate that, even if urban manufacturers contribute to a circular economy, they tend to produce at a small scale, making their (positive) impact on the city as a whole relatively insignificant.

There are two potential ways to increase the impact of urban manufacturers – scaling up the production of existing individual facilities, or increasing the total amount of urban manufacturers in the city. The barriers for scaling up the production of individual urban manufacturers is relatively well explored and summarized in this chapter. The issue of increasing the total amount of urban manufacturers in a city, which would entail creating infrastructure, institutions, and a support network for a thriving community of urban manufacturers, is relatively unexplored.

Further research could therefore involve answering the question, “what are the conditions (such as infrastructure, institutions, support network, policies) for creating a thriving circular urban manufacturing community?

3.5.4 Industries suitable for circular urban manufacturing

Literature and interviewees on both circular cities and urban manufacturing have specified industries that are suitable for circular or urban manufacturing processes. Finding the overlaps between the specified industries from both topics therefore gives insight into which sectors can act as drivers to scaling up circular and urban manufacturing activity. The industries that were specified by both circular cities and urban manufacturing experts are: construction and demolition, fashion, bio-based products, and electronics (Fratini et al., 2019; Gravagnuolo et al., 2019; Petit-Boix & Leipold, 2018; Sassen, 2009; Schrock & Wolf-Powers, 2019; Srai et al., 2016).

Urban manufacturing experts give further insight into the *attributes* of products that are suitable for urban manufacturing. In order to compensate for high rental costs, urban manufacturers often make products of high value, such as products that are customized, niche (Burggräf et al., 2019; Rachel Freeman et al., 2017; Unterfrauner et al., 2017), design-driven, and technology-driven (Interviewee E). Urban manufactured products also tend to be small (Interviewee C, E), have short life-times (Interviewee C, H), and are essential goods (Interviewee A, E). The table below provides a summary of products mentioned by authors and experts, as well as their attributes that make them suitable to be manufactured in urban areas.

TABLE 3.4 Summary of products and attributes suitable for circular urban manufacturing.

	high-value	small	design-driven	Custom-ized	essen-tial	tech-nology driven	niche	short life-times	perish-able	heavy
C&D [1]	x		x	x	x	x				x
fashion	x	x	x	x	x			x		
healthcare	x	x		x	x	x	x			
food	x	x			x			x	x	
electronics	x	x	x			x	x			
diamonds	x	x	x	x						
furniture	x		x	x						
plastic		x	x							

1 Construction and demolition.

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To summarize, the findings of this chapter point towards four further research directions: the geographical scales of the circular economy, the local embeddedness of urban manufacturers from the perspective of material flows, strategies for scaling up the impact of circular urban manufacturers, and industries suitable for circular urban manufacturing. Learning from our findings, we do not advocate for urban manufacturing of *all* products or the localization of *all* resource flows – that would be unrealistic and unsustainable. Instead, we recommend further research to identify resources that are suitable to be recirculated at the city level, and products that are suitable for locally embedded supply chains.

3.6 Conclusions

The aim of this research was to establish whether urban manufacturing is a viable strategy for developing a circular economy in cities by answering two research questions: (1) Does urban manufacturing contribute to circular economy in cities, and how? And (2) What are the drivers and barriers to circular urban manufacturing? The questions were answered through conducting a literature review of Life Cycle Assessments (LCAs) of urban manufacturing processes, interviews of experts within the fields of circular economy and urban manufacturing, and a literature review of drivers and barriers in both circular cities and urban manufacturing.

It was found that, while there is empirical evidence that urban manufacturing can reduce GHG emissions by reducing transportation distances and using waste as a resource, these claims come with a number of caveats. These caveats include the fact that transportation emissions contribute far less to GHG emissions than other production processes, that the scale of urban manufacturers is often too small to make an impact on the city as a whole, and that there are barriers to scaling up existing urban manufacturing activity.

This research then defined the drivers and barriers to circular urban manufacturing, and categorized them under the perspectives of “space”, “people”, and “flows”. Spatial drivers and barriers are related to the availability of industrial land in cities, which depends on the willingness and ability of municipalities to protect industrial land. People-related drivers and barriers are related to urban manufacturing businesses’ access to support networks, as well as their ability to scale up production while maintaining an urban location. Flow-related drivers and barriers are related to the availability and quality of local raw materials, including both municipal and industrial waste.

To conclude, while there is potential for urban manufacturing to contribute to circular cities, their current impact on the city as a whole is limited. Further research is needed to understand the conditions that allow urban manufacturers to scale up their production while remaining in the city.

Supplementary materials

The following are available online at https://www.mdpi.com/2071-1050/13/1/23/s1

1. Transcript of Interviews with Experts;
2. Interviews, Summary and Coding;
3. Literature, Summary and Coding;
4. LCAs of Urban Manufacturing Summary.

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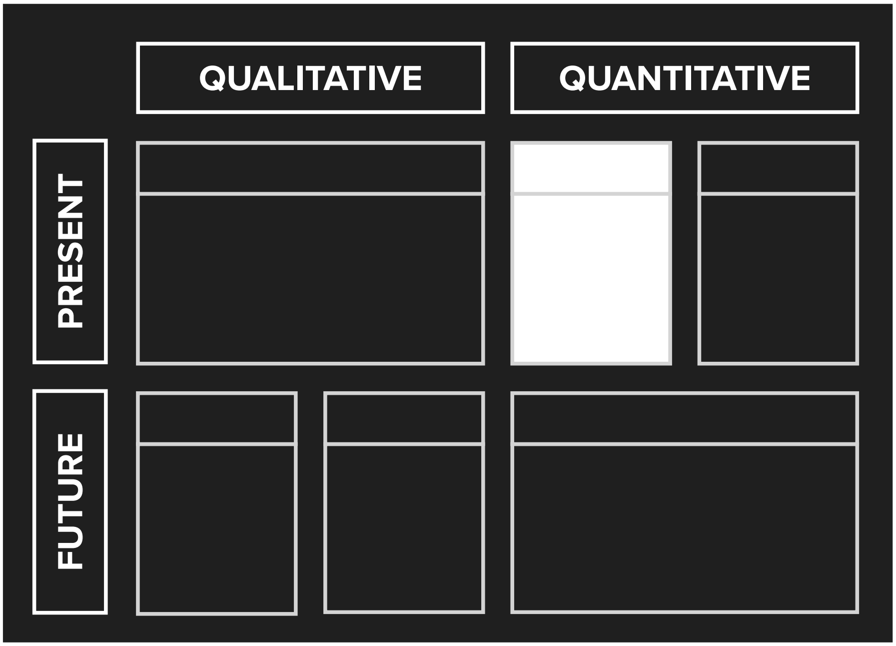
QUALITATIVE
QUANTITATIVE
PRESENT
FUTURE

4 Spatial factors for locations and scales of today

Based on the publication:
Circular maker city: A spatial analysis on factors affecting the presence of waste-to-resource organizations in cities
Tanya Tsui, Arjang Tajbakhsh, David Peck, Arjan van Timmeren
Published in Ecocity World Summit 2021-22 Conference Proceedings. Ecocity world summit 2021-22, Rotterdam.

ABSTRACT

In recent years, the concept of the circular economy in cities (or ‘circular cities’) has been gaining traction among policy makers and urban planners. One strategy for circular cities is to locally convert waste to resources, which could be enhanced by the presence of ‘circular makers’ in cities: waste-to-resource organizations such as manufacturers utilizing waste streams for their production processes. Existing literature has identified a number of drivers and barriers that affect the presence of circular makers in a city, but the discussion has less focus on spatial perspectives, and instead examines policies and strategies of cities as a whole, without zooming in to smaller scales to understand neighborhood spatial characteristics. The aim of this research is to verify drivers and barriers from existing literature by answering the research question: How do space, people, and flow-related characteristics of neighborhoods affect the location of secondary resources received by circular makers? The research question was answered by conducting spatial analysis on the waste flow dataset of the national waste registry of the Netherlands - using Moran’s I to understand spatial clustering of various material and industry types, and Pearson’s correlation coefficient to understand relationships between the factors and secondary resources received. It was found that two industrial sectors (construction and agriculture) and seven materials formed strong spatial patterns. For correlations in the construction industry, flow factors resulted in correlations at both the country and regional scale, space-related factors resulted in correlations only at the regional scale, and people-related factors resulted in no correlations.

KEYWORDS

circular cities, urban manufacturing, waste-to-resource flows, spatial analysis, sustainable cities, resource efficiency, eco-industrial development

4.1 Introduction

Cities have a large environmental impact - they consume 60-80% of natural resources globally, produce 50% of global waste, and 75% of greenhouse gas emissions (Hoballah et al., 2012). In recent years, transitioning to a circular economy has been proposed by policy makers as a potential solution for cities. While there is no common definition for the circular economy, it is, however, generally understood as a closed-loop system that employs circular processes such as reuse, refurbishing, remanufacturing, and recycling to convert waste into resources (European Commission, 2020). To implement a circular economy at a city level, one proposed approach is to encourage local industrial activities in or near cities, minimizing the importation of raw materials and reliance on global supply chains (Kirchherr et al., 2017). This would be enhanced by the presence of ‘circular makers’: organizations that use processed waste as a secondary resource. In this chapter, the word ‘maker’ is used rather than ‘manufacturer’ or ‘industry’, in order to include sectors that are not considered ‘industrial’ but still contribute to turning waste into resources, such as the construction and demolition industry or agricultural industry.

In the previous chapter (ch. 3), a literature review and expert interviews were conducted to identify the drivers and barriers that affect the presence of circular makers in an area. These included space-related factors such as the affordability of land; people-related factors such as level of education for the local population; and flow-related factors such as the availability of waste in the area (Tsui et al., 2020).

As a development from this previous research, this chapter aims to empirically verify drivers and barriers from existing literature by identifying the statistically significant factors that affect the presence of circular makers in a certain location. This will be done by using spatial statistical methods to analyze the waste flow dataset from the Dutch national waste registry, in order to understand the spatial characteristics of areas that contain circular makers receiving a high amount of secondary resources. The research question for this chapter is: How do space, people, and flow-related characteristics of neighborhoods affect the volume of secondary resources received? This research question is further divided into two sub-research questions: (1) Do the location of circular makers follow a spatial pattern? (2) What is the correlation between the amount of secondary resources received by circular makers in the construction industry, and the space, people, and flow-related factors?

Using spatial statistical methods, and the Netherlands as a case study, it was found that, for industry types, the construction and agricultural industry had the strongest spatial patterns. For material types, mixed wastes from sorting residues, vegetal wastes, mineral wastes, and fertilizers had the strongest spatial patterns. For correlations at the country level, flow factors had mild correlations, while the space and people-related factors had no correlations. When examining smaller regions surrounding hotspots, it was found that space and flow-related factors had mild correlations, while there were still no correlations for people-related factors.

4.2 Theoretical background

4.2.1 Overview of literature

Knowledge on the factors affecting the location of circular makers can be found in two domains - urban economic policy and industrial ecology; and two perspectives - ‘territorial’ and ‘company’. Studies from the ‘territorial’ perspective examine how the characteristics of a territory (such as population density or land value) have an effect on the location of companies. Studies from the ‘company’ perspective examine how characteristics of a company (such as type of industry, amount of materials processed) affect its location. While the fields of urban economic policy and economic geography tend to conduct studies from a ‘territorial’ perspective, industrial ecology studies tend to take a ‘company’ perspective.

4.2.1.1 Urban economic policy and economic geography

In the previous chapter (ch. 3), a literature review was conducted on the space, people, and flow-related drivers and barriers to the presence of circular makers in an urban area (Tsui et al., 2020). Many of the papers in the literature review originated from urban economic policy research on urban manufacturing, which studies how economic and urban planning policy affect the presence of making activities within urban areas. While there was limited understanding on circular making activities, this body of literature gives a good insight on drivers and barriers for the presence of making activities in cities.

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In terms of spatial factors, authors have found that the presence of making depends on the availability of affordable industrial land and manufacturing spaces (Hennelly et al., 2019), which in turn is affected by municipalities' protective industrial zoning strategies (Schrock & Wolf-Powers, 2019), as well as the level of ownership and control municipalities have over their land (Campbell-Johnston et al., 2019; Leigh & Hoelzel, 2012; Prendeville et al., 2018). A lack of industrial land can limit the availability for both circular infrastructure (such as spaces for storage, collection and recycling materials) (Williams, 2019b, 2019a), and manufacturing spaces (Doussard et al., 2018; Hennelly et al., 2019; Schrock & Wolf-Powers, 2019; Wolf-Powers et al., 2017).

For people-related factors, authors found that makers locate themselves in urban areas in order to be closer to existing customers and support networks. Customers of makers can include wealthy environmentally conscious customers interested in locally-produced goods (Hatuka et al., 2017; Sassen, 2009; Srai et al., 2016); design or technology driven companies in need of customized making or prototyping services (Sassen, 2009; Schrock & Wolf-Powers, 2019); as well as niche markets that require custom-made goods (Doussard et al., 2018; Unterfrauner et al., 2018). Support networks can include skilled workers and professionals (Burggräf et al., 2019; Schrock & Wolf-Powers, 2019; Wolf-Powers et al., 2017); experts, consultants, and universities (Hatuka et al., 2017); as well as marketing or business support (Wolf-Powers et al., 2017).

For flow-related factors, authors have argued that circular making is driven by availability of municipal and industrial waste. The accumulation of municipal waste in cities gives an opportunity to recycle waste locally at the city scale (Williams, 2019b), while industrial waste, which is higher in quality and quantity, gives more opportunity for circular processes to happen at an industrial scale (Tsui et al., 2020). The location of circular making is also driven by agglomeration of local production networks - circular makers tend to value proximity to large-scale traditional manufacturers (Hatuka et al., 2017; Hennelly et al., 2019; Millard et al., 2018; Schrock & Wolf-Powers, 2019), as well as local supply-chains of smaller-scale manufacturers (Sassen, 2009; Schrock & Wolf-Powers, 2019).

The urban economic policy literature summarized in the previous paragraph is connected to the larger field of economic geography, which established location theory of companies. Here, authors develop spatial statistical methods to investigate factors affecting company location, such as the local municipal tax rate, labor laws, accessibility, as well as the local population's education level. Common factors investigated by economic geographers are: labor (such as education, unemployment), public sector interventions (such as taxation, infrastructure,

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funding), geography (local climate, elevation, proximity to the coast) (Alañon-Pardo et al., 2018), accessibility (proximity to transport infrastructure) (Artal-Tur et al., 2013; Holl, 2004), as well as agglomeration (number of existing companies) (Head et al., 1995; Luo et al., 2020).

4.2.1.2 Industrial ecology

In the field of industrial ecology, authors have debated the benefits and trade-offs of different spatial scales of waste-to-resource flows - from industrial parks, to cities, to multi-city regions. Within this debate, some authors have explicitly identified the factors that allow for waste-to-resource exchanges to happen at a city or regional scale, advocating for the importance of industrial regions. Industrial ecology studies on circular makers mainly take the ‘company’ perspective, examining how the properties of a company (in terms of what materials and processes are being used) affect the geographical scale of its supply chain. For example, literature has found that the spatial scale of waste-to-resource companies is dependent on a variety of economic reasons with spatial constraints, such as transport costs, density of waste in an area, and service provision (Lyons, 2005, 2008).

Authors have also advocated for the industrial region (~30 km radius) as a promising unit for waste-to-resource exchange for eco-industrial development. According to case studies conducted in Germany, the industrial region is large enough to include a diverse collection of companies that would allow for waste-to-resource exchange, but small enough to minimize transportation costs (Sterr & Ott, 2004). Other empirical spatial studies on industrial symbiosis in the United Kingdom and China also found that the average distance between two industrial symbiosis partners was approximately 30 km (Jensen et al., 2011; Shi et al., 2010).

Additionally, authors have also examined how the properties of a material (such as its density or economic value) affects the distance it travels for waste-to-resource exchanges. Some authors found through case studies that high-value, low-volume goods are not spatially constrained and can travel long distances (Chertow et al., 2008). However, others found that there was no correlation between the weight or value of materials and the distance they traveled. Instead, it was dependent on the difficulty of reuse (Jensen et al., 2011).

4.2.2 Research gaps

Economic geography has a well-established body of research on factors affecting company location from a territorial perspective, which is supported by well developed and sophisticated spatial statistical models. However, economic geography literature has understandably paid less attention to factors related to spatial planning, such as accessibility, density, land use, land value, or level of urbanization. The amount of studies on circular makers is also limited, although factors affecting the location of manufacturing companies have been well described. Moreover, economic geography studies tend to examine cities or provinces as a whole (areas that have a diameter of around 30 - 100km), without zooming into smaller scales (3 - 10km) to find neighborhood attributes that could explain why circular makers are clustered in certain areas in a city and not another.

Industrial ecology literature, on the other hand, provides a deeper understanding of circular makers, as well as the spatial constraints of various waste-to-resource processes. However, studies lack a 'territorial' perspective, which explains how characteristics of a geographical territory (such as land value, accessibility, average income) could attract circular makers.

4.2.3 Research aim and questions

The aim of this research is to use spatial analysis methods with a territorial perspective from economic geography, as a tool to understand location patterns of circular makers in the Netherlands. The hope is to provide an additional perspective to existing knowledge on circular makers in industrial ecology, as well as insights to spatial planning for a circular economy at the city scale.

This chapter's research question is: How do space, people, and flow-related characteristics of neighborhoods affect the location of secondary resources received by circular makers? In other words, why do secondary resources end up in one neighborhood and not another, and which space, people, or flow-related characteristics are they affected by? The two sub-research questions are: (1) Do the location of circular makers follow a spatial pattern? (2) What is the correlation between the amount of secondary resources received by circular makers in the construction industry, and the space, people, and flow-related factors?

4.3 Methodology

This research will use data from the national waste registry of the Netherlands to understand the level of spatial clustering of circular makers using spatial autocorrelation (sub-research question 1), and find correlations between space, people, and flow-related factors and the amount of secondary resources received by circular makers in each postcode (sub-research question 2).

4.3.1 Data source and processing

This study will utilize data from the national waste registry of the Netherlands (Dutch Ministry of Infrastructure and Water Management, 2019; Sileryte et al., 2022), which records all waste flows larger than 50kg in the Netherlands that are processed by waste management companies, and includes information on the location of waste producers, processors, and secondary resource receivers; as well as the weight and material type of the waste flow. This study focused on the location of 'first receivers' ('eerste afnemers' in Dutch), which are non-waste management companies that receive processed waste as a secondary resource from waste companies. The focus was on 'first receivers' because they most resembled the description of 'circular makers', coming from various 'making' industries, such as construction and agriculture.

Using the LMA dataset, the amount of secondary resources received were calculated for each level 4 postcode in the Netherlands. Level 4 postcodes (e.g. 1011) were chosen instead of level 2 (e.g. 10) or level 6 (e.g. 1011 AA) because they were small enough to explain neighborhood differences (with a diameter of approximately 2 - 5 km), and large enough to prevent computational strain during spatial analysis. The secondary resources received per postcode were further categorized by industry and material type. Industry types were defined by the standard industry grouping code (SBI, Standaard Bedrijfsindeling) of the first receiver, which was found using an SBI code dataset from the Dutch chamber of commerce. Material types were already defined in the LMA dataset, using the European waste code (EWC) and the combined nomenclature code.

Finally, some flows in the LMA dataset were deemed as 'invalid' because the location of the first receiver in the dataset did not represent the true location of reuse, but rather the location of the headquarters of the company. These 'invalid' flows were removed with the help of waste experts from the Rijkswaterstaat, the Dutch government agency for public works. A full explanation of the data's limitations can be found in the limitations section.

4.3.2 Spatial analysis

4.3.2.1 Spatial autocorrelation

Spatial autocorrelation was used to understand whether the location of circular makers create a spatial pattern. Spatial autocorrelation describes the presence of systematic spatial variation in a variable. A positive spatial autocorrelation of a dataset would mean that areas closer together are more similar than areas far apart from each other. Moran's I, a measure of spatial autocorrelation, was used to indicate the level of spatial clustering for the top ten industries and materials in the dataset. A Monte Carlo method was used to estimate the statistical significance of spatial clustering. For each industry and material type, the Moran's I was calculated to quantify the level of clustering for the amount (kg) received per postcode - this is the 'observed Moran's I'. Then, in a simulation, the values were randomly reassigned to other postcodes, and the Moran's I is calculated again. This process of simulation was repeated 999 times, creating 999 simulated Moran's I's. Finally, the observed and simulated Moran's Is were compared, and if the observed Moran's I value is higher than 99.9% of the simulated Moran's Is (p-value of 0.001), it was considered as statistically significant. A p-value of 0.001 means that there is a 99.9% chance that the location of circular makers follow a spatial pattern and are not randomly distributed through space.

For each industry and material type, Moran's I was also used to identify the "hotspots, cold spots, doughnuts, and diamonds". "Hotspots" are high value areas surrounded by high value neighbors, "cold spots" are low value areas surrounded by low value neighbors, "doughnuts" are low value areas surrounded by high value neighbors, and "diamonds" are high value areas surrounded by low value neighbors.

Using spatial autocorrelation, industry and material types with significant spatial clustering were identified. With these results, a comparison was made between the industry and material perspective to understand which perspective is more strongly influenced by space.

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4.3.2.2 Correlations

The step after spatial autocorrelation was to find correlations between space, people, and flow-related factors and the amount (kg) of secondary resources received by the construction industry at both the country and regional scale. In order to find correlations, space, people, and flow-related factors were identified from our previous research and industrial ecology and economic geography literature. The factors were then transformed into quantitative values that could be attributed to each postcode in the Netherlands. For example, the factor 'presence of industrial land' was transformed into the variables 'percentage of industrial land' and 'distance (km) from nearest industrial land'. The chosen factors are shown below in Table 4.1.

TABLE 4.1 Space, people, and flow-related factors chosen from existing literature.

Space-related factors	People related factors	Flow-related factors
Distance to nearest airport, seaport, freight train station, main road, industrial land; distance to nearest urban area, population density, area of industrial land, average household price	Percentage of people with low and high income, distance to nearest university, number of universities within 10km radius	Total amount of secondary resources received, waste processed, waste produced, amount received within 0-4km, 4-10km, 10-30km, 30-50km, and >50km

Once the variables were identified, the variables with log-normal distributions were log transformed so that they followed a normal distribution. Then, the spatial lag of the variables was calculated, with weight distances of 4, 10, and 30km. A spatial lag is a variable that indicates the average of the neighboring values of a location. This allows for an understanding of not only the immediate attributes of each postcode, but the general attributes of its neighborhood at different spatial scales.

Finally, the Pearson's correlation coefficient was used to calculate the correlation between the amount of secondary resources received (kg) by the construction industry, and the space, people, and flow-related variables, including the spatial lag variables with weight distances of 4, 10, and 30km. A correlation value between 0.3 - 0.5 was considered a mild correlation, between 0.5 - 0.7 a moderate correlation, and between 0.7 - 1 a high correlation. Correlations were calculated for the whole of the Netherlands, as well as two smaller areas in the country that were hotspots for construction industry receivers - regions around the cities of Amersfoort (region A) and Eindhoven (region B). Correlations were also calculated for the data both with and without zero values.

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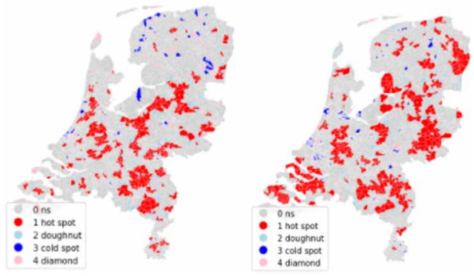
4.4 Results

4.4.1 Spatial autocorrelation

When data points were categorized by industry type, two of the top ten industry types, construction and agriculture, had a Moran’s I of higher than 0.1 and p-value lower than 0.001. A summary of the top 10 industries in the LMA dataset, their Moran’s I values, and p-values are shown below in Table 4.2. The hot spots, cold spots, doughnuts, and diamonds of the construction and agriculture industry are shown below in Figure 4.1.

TABLE 4.2 Moran’s I and p-values of top 10 industry types by weight.

Rank (by weight)	Industry code and name	Observed Moran’s I	p-value
1	C - Manufacturing	0.04	**0.001**
2	E - Water supply; sewage, waste management and remediation activities	0.02	0.012
3	**F - Construction**	**0.13**	**0.001**
4	G - Wholesale and retail trade; repair of motor vehicles and motorcycles	0.04	**0.001**
5	**A - agriculture**	**0.26**	**0.001**
6	H - Transportation and storage	0.05	**0.001**
7	K - financial institutions	0.05	**0.001**
8	M - Consultancy, research and other specialized business services	0.03	0.01
9	B - Mining and quarrying	0.03	0.012
10	D - electricity, gas, steam and air conditioning supply	-0.0	0.468



The maps were created using local Moran’s I, which highlight four types of areas that are statistically significant: hot spots (red), locations with high reuse rates surrounded by high reuse locations; cold spots (blue), locations with low reuse rates surrounded by low reuse locations; diamonds (pink), locations with high reuse rates surrounded by low reuse locations; and doughnuts (light blue), locations with low reuse rates surrounded by high reuse locations.

FIG. 4.1 Hot spot maps for waste reuse in the construction (left) and agricultural (right) industry.

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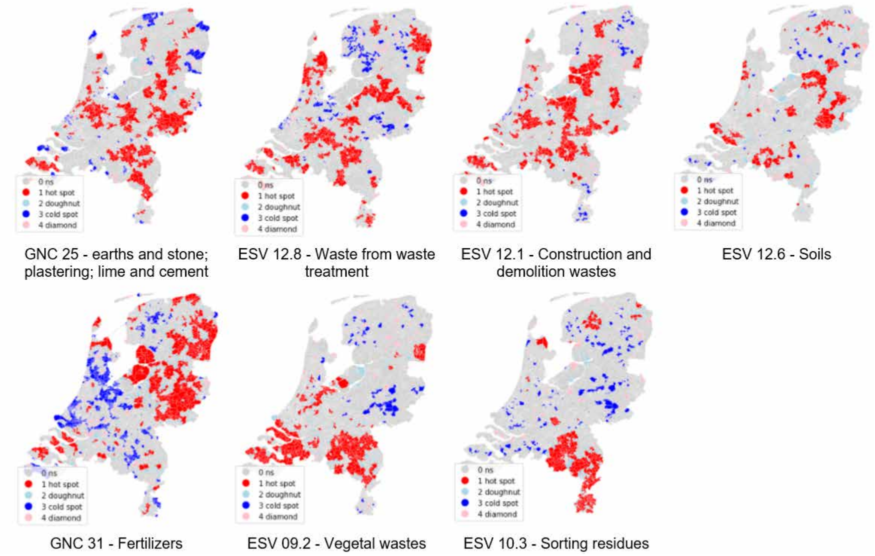
When data points were categorized by material type, seven of the top ten materials had a Moran's I of higher than 0.1 and p-value lower than 0.001. A summary of the top 10 materials in the LMA dataset, their Moran's I values, and p-values are shown below in Table 4.3. The hot spots, cold spots, doughnuts, and diamonds of the seven materials with a statistically significant Moran's I is shown below in Figure 4.2.

TABLE 4.3 Moran's I and p-values for top 10 material types by weight.

Rank (by weight)	Material code and name	Observed Moran's I	p-value
1	**GNC 25 - Salt; Sulphur; earths and stone; plastering materials; lime and cement**	**0.23**	**0.001**
2	**ESV 12.8 - Waste from waste treatment**	**0.19**	**0.001**
3	**ESV 12.1 - Construction and demolition wastes**	**0.2**	**0.001**
4	ESV 07.2 - Paper and cardboard wastes	0.03	0.003
5	**ESV 12.6 - Soils**	**0.14**	**0.001**
6	ESV 06.1 - Metal wastes, ferrous	0.04	**0.001**
7	**GNC 31 - Fertilizers**	**0.21**	**0.001**
8	**ESV 09.2 - Vegetal wastes**	**0.26**	**0.001**
9	**ESV 10.3 - Sorting residues**	**0.25**	**0.001**
10	ESV 06.2 - Metal wastes, non-ferrous	0.04	**0.001**



GNC 25 - earths and stone; plastering; lime and cement

ESV 12.8 - Waste from waste treatment

ESV 12.1 - Construction and demolition wastes

ESV 12.6 - Soils

GNC 31 - Fertilizers

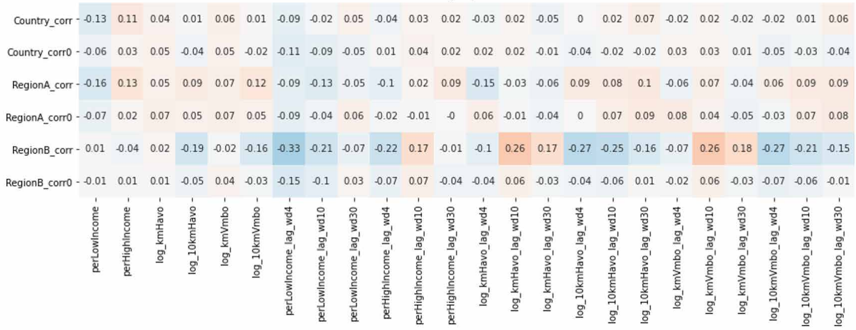
ESV 09.2 - Vegetal wastes

ESV 10.3 - Sorting residues

FIG. 4.2 Hot spot maps for waste reuse, with data categorized into material types. The methods used were the same as methods for waste reuse categorized by industry, as explained in the description for Figure 1.

4.4.2 Correlations

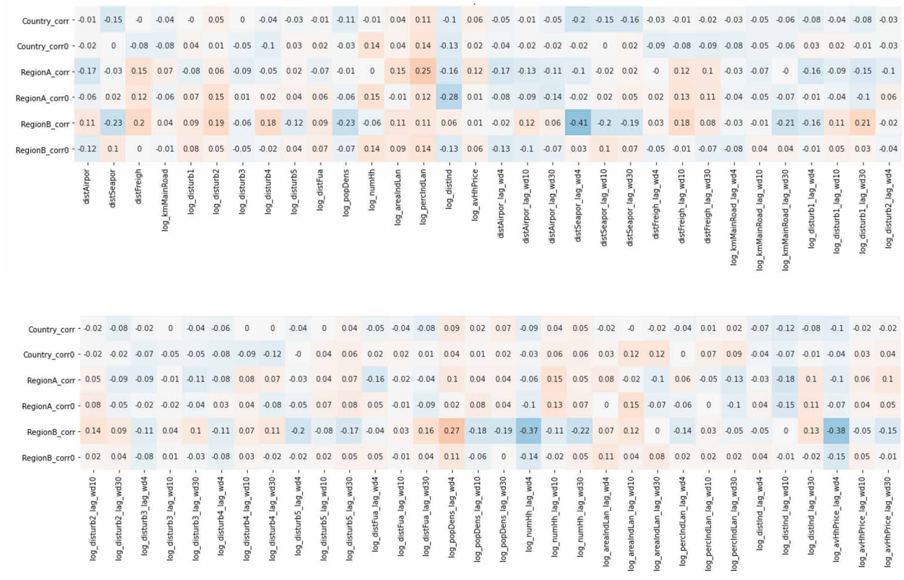
Once the spatial autocorrelation was conducted, the construction industry was chosen to investigate the correlations between amount (kg) of secondary resources received and the previously chosen space, people, and flow-related variables. Correlations for space, people, and flow related factors are shown below in Figures 4.3, 4.4, and 4.5. In terms of correlations for the whole country, some flow factors (total amount of secondary resources received (regardless of industry and material), and total amount of waste processed) had a mild positive correlation. Amount received by the construction industry within 0-4km, 30-50km, and >50km had mild positive correlations, and amount received by the construction industry within 4-10km and 10-30km had moderate positive correlations. There were no correlations for the space and people-related factors, and no correlations for the spatial lag values of the space, people, and flow factors.



	perLowIncome	perHighIncome	log_kmHavo	log_10kmHavo	log_kmVmbo	log_10kmVmbo	perLowIncome_lag_wd4	perLowIncome_lag_wd10	perLowIncome_lag_wd30	perHighIncome_lag_wd4	perHighIncome_lag_wd10	perHighIncome_lag_wd30
Country_corr	-0.13	0.11	0.04	0.01	0.06	0.01	-0.09	-0.02	0.05	-0.04	0.03	0.02
Country_corr0	-0.06	0.03	0.05	-0.04	0.05	-0.02	-0.11	-0.09	-0.05	0.01	0.04	0.02
RegionA_corr	-0.16	0.13	0.05	0.09	0.07	0.12	-0.09	-0.13	-0.05	-0.1	0.02	0.09
RegionA_corr0	-0.07	0.02	0.07	0.05	0.07	0.05	-0.09	-0.04	0.06	-0.02	-0.01	-0
RegionB_corr	0.01	-0.04	0.02	-0.19	-0.02	-0.16	-0.33	-0.21	-0.07	-0.22	0.17	-0.01
RegionB_corr0	-0.01	0.01	0.01	-0.05	0.04	-0.03	-0.15	-0.1	0.03	-0.07	0.07	-0.04

	log_kmHavo_lag_wd4	log_kmHavo_lag_wd10	log_kmHavo_lag_wd30	log_10kmHavo_lag_wd4	log_10kmHavo_lag_wd10	log_10kmHavo_lag_wd30	log_kmVmbo_lag_wd4	log_kmVmbo_lag_wd10	log_kmVmbo_lag_wd30	log_10kmVmbo_lag_wd4	log_10kmVmbo_lag_wd10	log_10kmVmbo_lag_wd30
Country_corr	-0.03	0.02	-0.05	0	0.02	0.07	-0.02	0.02	-0.02	-0.02	0.01	0.06
Country_corr0	0.02	0.02	-0.01	-0.04	-0.02	-0.02	0.03	0.03	0.01	-0.05	-0.03	-0.04
RegionA_corr	-0.15	-0.03	-0.06	0.09	0.08	0.1	-0.06	0.07	-0.04	0.06	0.09	0.09
RegionA_corr0	0.06	-0.01	-0.04	0	0.07	0.09	0.08	0.04	-0.05	-0.03	0.07	0.08
RegionB_corr	-0.1	0.26	0.17	-0.27	-0.25	-0.16	-0.07	0.26	0.18	-0.27	-0.21	-0.15
RegionB_corr0	-0.04	0.06	-0.03	-0.04	-0.06	0.01	-0.02	0.06	-0.03	-0.07	-0.06	-0.01

FIG. 4.3 Correlations for people factors. Correlations between amount of waste reused and local people-related factors (such as income and level of education of the local population) were calculated at both the country and regional scale. No correlations were found except for in region B.



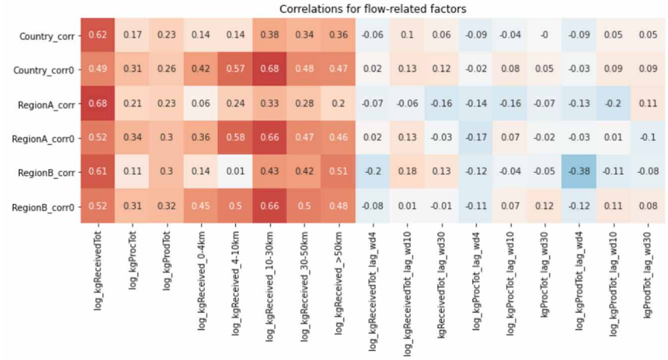
	distAirpor	distSeapor	distFreigh	log_kmMainRoad	log_disturb1	log_disturb2	log_disturb3	log_disturb4	log_disturb5	log_distFua	log_popDens	log_numHh	log_areaIndLan	log_percIndLan	log_distInd	log_avHhPrice
Country_corr	-0.01	-0.15	-0	-0.04	-0	0.05	0	-0.04	-0.03	-0.01	-0.11	-0.01	0.04	0.11	-0.1	0.06
Country_corr0	-0.02	0	-0.08	-0.08	0.04	0.01	-0.05	-0.1	0.03	0.02	-0.03	0.14	0.04	0.14	-0.13	0.02
RegionA_corr	-0.17	-0.03	0.15	0.07	-0.08	0.06	-0.09	-0.05	0.02	-0.07	-0.01	0	0.15	0.25	-0.16	0.12
RegionA_corr0	-0.06	0.02	0.12	-0.06	0.07	0.15	0.01	0.02	0.04	0.06	-0.06	0.15	-0.01	0.12	-0.28	0.01
RegionB_corr	0.11	-0.23	0.2	0.04	0.09	0.19	-0.06	0.18	-0.12	0.09	-0.23	-0.06	0.11	0.11	0.06	0.01
RegionB_corr0	-0.12	0.1	0	-0.01	0.08	0.05	-0.05	-0.02	0.04	0.07	-0.07	0.14	0.09	0.14	-0.13	0.06

	distAirpor_lag_wd4	distAirpor_lag_wd10	distAirpor_lag_wd30	distSeapor_lag_wd4	distSeapor_lag_wd10	distSeapor_lag_wd30	distFreigh_lag_wd4	distFreigh_lag_wd10	distFreigh_lag_wd30	log_kmMainRoad_lag_wd4	log_kmMainRoad_lag_wd10	log_kmMainRoad_lag_wd30	log_disturb1_lag_wd4	log_disturb1_lag_wd10	log_disturb1_lag_wd30	log_disturb2_lag_wd4
Country_corr	-0.05	-0.01	-0.05	-0.2	-0.15	-0.16	-0.03	-0.01	-0.02	-0.03	-0.05	-0.06	-0.08	-0.04	-0.08	-0.03
Country_corr0	-0.04	-0.02	-0.02	-0.02	0	0.02	-0.09	-0.08	-0.09	-0.08	-0.05	-0.06	0.03	0.02	-0.01	-0.03
RegionA_corr	-0.17	-0.13	-0.11	-0.1	-0.02	0.02	-0	0.12	0.1	-0.03	-0.07	-0	-0.16	-0.09	-0.15	-0.1
RegionA_corr0	-0.08	-0.09	-0.14	-0.02	0.02	0.05	0.02	0.13	0.11	-0.04	-0.05	-0.07	-0.01	-0.04	-0.1	0.06
RegionB_corr	-0.02	0.12	0.06	-0.41	-0.2	-0.19	0.03	0.18	0.08	-0.03	-0.01	-0.21	-0.16	0.11	0.21	-0.02
RegionB_corr0	-0.13	-0.1	-0.07	0.03	0.1	0.07	-0.05	-0.01	-0.07	-0.08	0.04	0.04	-0.01	0.05	0.03	-0.04

	log_disturb2_lag_wd10	log_disturb2_lag_wd30	log_disturb3_lag_wd4	log_disturb3_lag_wd10	log_disturb3_lag_wd30	log_disturb4_lag_wd4	log_disturb4_lag_wd10	log_disturb4_lag_wd30	log_disturb5_lag_wd4	log_disturb5_lag_wd10	log_disturb5_lag_wd30	log_distFua_lag_wd4	log_distFua_lag_wd10	log_distFua_lag_wd30	log_popDens_lag_wd4	log_popDens_lag_wd10
Country_corr	-0.02	-0.08	-0.02	0	-0.04	-0.06	0	0	-0.04	0	0.04	-0.05	-0.04	-0.08	0.09	0.02
Country_corr0	-0.02	-0.02	-0.07	-0.05	-0.05	-0.08	-0.09	-0.12	-0	0.04	0.06	0.02	0.02	0.01	0.04	0.01
RegionA_corr	0.05	-0.09	-0.09	-0.01	-0.11	-0.08	0.08	0.07	-0.03	0.04	0.07	-0.16	-0.02	-0.04	0.1	0.04
RegionA_corr0	0.08	-0.05	-0.02	-0.02	-0.04	0.03	0.04	-0.08	-0.05	0.07	0.08	0.05	-0.01	-0.09	0.02	0.08
RegionB_corr	0.14	0.09	-0.11	0.04	0.1	-0.11	0.07	0.11	-0.2	-0.08	-0.17	-0.04	0.03	0.16	0.27	-0.18
RegionB_corr0	0.02	0.04	-0.08	0.01	-0.03	-0.08	0.03	-0.02	-0.02	0.02	0.05	0.05	-0.01	0.04	0.11	-0.06

	log_popDens_lag_wd30	log_numHh_lag_wd4	log_numHh_lag_wd10	log_numHh_lag_wd30	log_areaIndLan_lag_wd4	log_areaIndLan_lag_wd10	log_areaIndLan_lag_wd30	log_percIndLan_lag_wd4	log_percIndLan_lag_wd10	log_percIndLan_lag_wd30	log_distInd_lag_wd4	log_distInd_lag_wd10	log_distInd_lag_wd30	log_avHhPrice_lag_wd4	log_avHhPrice_lag_wd10	log_avHhPrice_lag_wd30
Country_corr	0.07	-0.09	0.04	0.05	-0.02	-0	-0.02	-0.04	0.01	0.02	-0.07	-0.12	-0.08	-0.1	-0.02	-0.02
Country_corr0	0.02	-0.03	0.06	0.06	0.03	0.12	0.12	0	0.07	0.09	-0.04	-0.07	-0.01	-0.04	0.03	0.04
RegionA_corr	0.04	-0.06	0.15	0.05	0.08	-0.02	-0.1	0.06	-0.05	-0.13	-0.03	-0.18	0.1	-0.1	0.06	0.1
RegionA_corr0	0.04	-0.1	0.13	0.07	0	0.15	-0.07	-0.06	0	-0.1	0.04	-0.15	0.11	-0.07	0.04	0.05
RegionB_corr	-0.19	-0.37	-0.11	-0.22	0.07	0.12	0	-0.14	0.03	-0.05	-0.05	0	0.13	-0.38	-0.05	-0.15
RegionB_corr0	0	-0.14	-0.02	0.05	0.11	0.04	0.08	0.02	0.02	0.02	0.04	-0.01	-0.02	-0.15	0.05	-0.01

FIG. 4.4 Correlations for space factors. Correlations between amount of waste reused and local space-related factors (such as distance from industrial land or transportation infrastructure) were calculated at both the country and regional scale. Mild to moderate correlations were found at the regional scale, for both regions A and B.



Correlations for flow-related factors

	log_kgReceivedTot	log_kgProcTot	log_kgProdTot	log_kgReceived_0-4km	log_kgReceived_4-10km	log_kgReceived_10-30km	log_kgReceived_30-50km	log_kgReceived_>50km	log_kgReceivedTot_lag_wd4	log_kgReceivedTot_lag_wd10	kgReceivedTot_lag_wd30	log_kgProcTot_lag_wd4	log_kgProcTot_lag_wd10	kgProcTot_lag_wd30	log_kgProdTot_lag_wd4	log_kgProdTot_lag_wd10	kgProdTot_lag_wd30
Country_corr	0.62	0.17	0.23	0.14	0.14	0.38	0.34	0.36	-0.06	0.1	0.06	-0.09	-0.04	-0	-0.09	0.05	0.05
Country_corr0	0.49	0.31	0.26	0.42	0.57	0.68	0.48	0.47	0.02	0.13	0.12	-0.02	0.08	0.05	-0.03	0.09	0.09
RegionA_corr	0.68	0.21	0.23	0.06	0.24	0.33	0.28	0.2	-0.07	-0.06	-0.16	-0.14	-0.16	-0.07	-0.13	-0.2	0.11
RegionA_corr0	0.52	0.34	0.3	0.36	0.58	0.66	0.47	0.46	0.02	0.13	-0.03	-0.17	0.07	-0.02	-0.03	0.01	-0.1
RegionB_corr	0.61	0.11	0.3	0.14	0.01	0.43	0.42	0.51	-0.2	0.18	0.13	-0.12	-0.04	-0.05	-0.38	-0.11	-0.08
RegionB_corr0	0.52	0.31	0.32	0.45	0.5	0.66	0.5	0.48	-0.08	0.01	-0.01	-0.11	0.07	0.12	-0.12	0.11	0.08

FIG. 4.5 Correlations for flow factors. Correlations between amount of waste reused and local flow-related factors (such as amount of waste produced or processed in the local area) were calculated at both the country and regional scale. Mild to moderate correlations were found at both the country and regional scale.

For smaller areas surrounding hotspots, more correlations appeared, although some correlation values differed between region A and B. For the flow factors in both regions A and B, additional mild positive correlation was found for the amount of waste produced, and a mild negative correlation was found for average amount of waste produced within 4km. For the space-related factors in region A, a moderate negative correlation was found for the average distance from the nearest industrial land within a 10km radius. For region B, mild positive correlations were found for distance from nearest industrial land and the average percentage of industrial land within a 10km radius; and mild negative correlations were found for average distance to nearest seaport for postcodes within a 10km radius, and average household price for postcodes within a 4km radius. For people-related factors, no correlations appeared for region A, and a mild negative correlation was found for the average percentage of people with low income for postcodes within a 4km radius.

4.5 Discussion

4.5.1 Interpretation of results

4.5.1.1 Spatial autocorrelation results

When looking at the spatial autocorrelation results for the top 10 industries and materials, it can be seen that categorizing flows according to material led to more types with spatial clustering. In other words, flows categorized by material type (e.g. cement, vegetal wastes) instead of industry type (e.g. construction, agriculture) formed stronger spatial patterns. This might mean that companies using similar materials (e.g. wood) tend to cluster together regardless of what industry they are in (e.g. manufacturing, construction); whereas companies in similar industries (e.g. construction) do not cluster together regardless of what materials they use (wood, steel, cement). Thus, the spatial patterns in the Netherlands seem to be driven more by material than by industry.

This finding contributes to the existing discussion in industrial ecology literature on using a materials versus industry perspective when conducting material flow analysis. In the Handbook of Industrial Ecology, Bringezu and Moriguchi provided

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an overview of material flow analyses conducted by industrial ecologists, and separated them by materials versus industrial categorizations (Bringezu and Moriguchi, 2002). They found that studies on materials leaned towards a technical engineering perspective and were useful for predicting possible effects of new technologies on material management; while studies on industrial sectors leaned towards a socio-economic perspective and were useful when comparing sectors to inform policy (Ayres & Ayres, 2002). While the aim of this study is to provide insights to spatial planning policy, which would favor an industrial perspective, the spatial autocorrelation results found that a material perspective forms stronger spatial patterns. This is a tension that should be addressed in future research.

From the results, it can be seen that the level of spatial clustering for a flow type is not entirely related to the total amount (kg) of that flow type in the LMA data. This suggests that properties other than volume (e.g. value, processing type) may have an effect on the amount of spatial clustering. Finally, the results show that 6 material types and 2 industries with statistically significant Moran's Is, and are not randomly distributed through space. There is therefore benefit from conducting spatial analysis of these industries and materials, because their spatial clustering suggests that they are affected by location-related factors.

4.5.1.2 Country-wide and regional correlations

The results show that, in general, more correlations were found for smaller regions around hotspots rather than the Netherlands as a whole. Moreover, some factors' correlations differed between region A and B. This suggests that there are very few trends (only some flow-related factors) that can be generalized throughout the whole country. Instead, these trends vary from region to region. This may be because the amount of materials received is not a continuous variable across space and results in many postcodes with no value. As a result, areas with 'advantageous' spatial factors, might not have received any materials. There might also be other non-spatial reasons for the location of secondary resource flows, such as historical, economic, or even personal factors.

Flow-related factors had mild correlations at both the country and regional level. This suggests that agglomeration within the secondary resources supply chain plays a role in the location of secondary resource receiving circular makers. The correlations suggest that supply chain actors tend to attract each other and cluster together to form agglomerations, or that there is another hidden factor that might be attracting waste producers, processors, and receivers to similar locations.

At the country level, there were no correlations found for the flow-related spatial lag factors. This suggests that co-location of secondary resource supply chain actors happens at the scale of a postcode (around 2-5km), but doesn't extend beyond the neighborhood, region, or city (4, 10, 30km).

Space-related factors had no correlations at the country level, but mild correlations at the regional level, although correlations differed between region A and B. This suggests that the effect of spatial factors varies from region to region. However, it is worth noting that distance from nearest industrial land is a common factor for regional A and B. Finally, people-related factors had no correlations at the country and regional level. This suggests that the location of secondary resources is not related to attributes of the population.

4.5.2 Limitations

4.5.2.1 Limitations of the LMA dataset

The results of this study is limited by the dataset used, which contained the waste data of the national waste registry (LMA) of the Netherlands. Firstly, the LMA data is limited from a 'waste management' perspective. A waste flow is only recorded in the LMA dataset if it goes through a waste management company, which means that industrial symbiosis exchanges between non-waste management companies are not included. As a result, most of the flows analyzed in this study have been processed with low-value circular economy processes such as recycling.

This study is also limited by the quality of data collected by the LMA on the location of circular makers (called 'first receivers' in the dataset). For many entries, the location recorded for the first receivers do not represent the true location of reuse, but rather the location of the headquarters of the first receiver. Around 30% of flows in the construction industry were considered to be invalid. This means that the final dataset that was analyzed for this study contained many 'untrue' zero values, which skewed the results for both the spatial autocorrelation and correlations. Moreover, around 20% of the data (by weight) could not be matched with the correct SBI code, meaning that for 20% of the flows, the industrial sector remains unknown. This could have contributed to the lower performance of the industrial perspective for the spatial autocorrelation part of the study.

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4.5.2.2 Limitations of methods

The results of this study are also limited to the spatial analysis methods used to analyze the dataset. Moran's I values for each industry and material type were only calculated at the country scale. There is a chance that flow types with stronger spatial clustering at the city or regional level, were not captured by the country-wide Moran's I values. In other words, if the same Moran's I method was conducted on a province or city, the level of spatial clustering for the industry and material flows might have been different.

In this study, the Pearson's correlation coefficient was used to identify correlation between space, people, and flow related factors and secondary resources received. Pearson's correlation only detects linear relationships, so more complex, non-linear relationships between variables have not been captured in the results. Moreover, correlation does not equal causation. For example, a positive correlation between A and B might mean that the A caused an increase in B; but it could also mean that B caused A, or that there is a third hidden factor that affects both A and B, that remains undetected in this study.

4.6 Conclusion

4.6.1 Summary of research

In conclusion, this chapter aims to provide a spatial understanding on the presence of circular makers in cities by answering the research question: How do space, people, and flow-related characteristics of neighborhoods in the Netherlands affect the location of secondary resources received by circular makers in the Netherlands? The research question was answered by conducting spatial analysis on the waste flow dataset of the national waste registry of the Netherlands. Firstly, the level of spatial clustering of flows was examined by calculating the Moran's I value of the top ten materials and industries in the dataset. Then, correlations between space, people, and flow factors and the amount of secondary resources received by the construction industry were identified by calculating the Pearson's correlation coefficient on both the variables and their spatial lag with weight distance of 4, 10, and 30km.

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It was found that two industries (construction and agriculture) and seven materials formed strong spatial patterns with statistically significant Moran's I values. For correlations for amount received for the construction industry, flow factors resulted in correlations at both the country and regional scale, space-related factors resulted in correlations only at the regional scale, and people-related factors resulted in no correlations.

4.6.2 Recommendations for further research

Recommended further research directions respond to findings of this study, which is that the material perspective seems to form stronger spatial patterns than the industry perspective, and that there is a lack of trends that operate at a country level, but instead, trends seem to vary from region to region.

Since the materials perspective led to stronger spatial clustering, an investigation into the correlations for the material perspective could be beneficial. Additionally, the structure of the LMA data makes it easier to use the material perspective to trace flows from waste production, to processing, to receiving. This allows the possibility of extending the study beyond 'first receivers' or circular makers, to the entire waste-to-resource supply chain.

In response to the lack of spatial trends on the country level, other spatial analysis methods can be used to take into account regional level spatial trends. Firstly, instead of examining the entire dataset (~80% zero values), future research can examine only the statistically significant hotspots, cold-spots, doughnuts, and diamonds resulting from the spatial autocorrelation analysis. K-means clustering, which categorizes data into 'clusters' according to their attributes, can then be used to identify different 'types' or 'clusters' of hot spots, cold spots, doughnuts, and diamonds according to their space, people, and flow-related attributes. Geographically weighted regression (GWR), on the other hand, is a type of linear regression that takes into account the fact that dynamics between factors can vary across geographical space. Instead of creating one formula to describe the entire dataset (like linear regression), GWR creates one formula for each postcode to describe what is happening within its neighborhood. Using GWR, it is possible to understand how the effect of space, people, and flow factors changes across space.

4.6.3 Contributions

The findings and methodology of this chapter is an attempt to show an example of using well-established spatial analysis methods from the field of economic geography and applying them to the topic of circular makers, in order to expand the existing discussion in industrial ecology on waste-to-resource flows at the city scale. While existing circular cities literature has a stronger emphasis on policy, governance, and material flows, this chapter hopes to contribute a spatial perspective to understanding the topic. The spatial perspective of this chapter allows for a more detailed understanding of the locations of waste-to-resource flows at the neighborhood scale, as opposed to the municipal, provincial, or even national scale; and also allows researchers to look beyond administrative and municipal boundaries when analyzing material flows.

Additionally, this chapter investigated more factors affecting the location of circular makers from the perspective of spatial planning, such as population density, land use, land value, and accessibility. With further development, the hope is that this line of research could ultimately inform spatial policy, allowing existing circular city plans of municipalities to expand their reach beyond governance and economic policy, towards spatial and regional planning.

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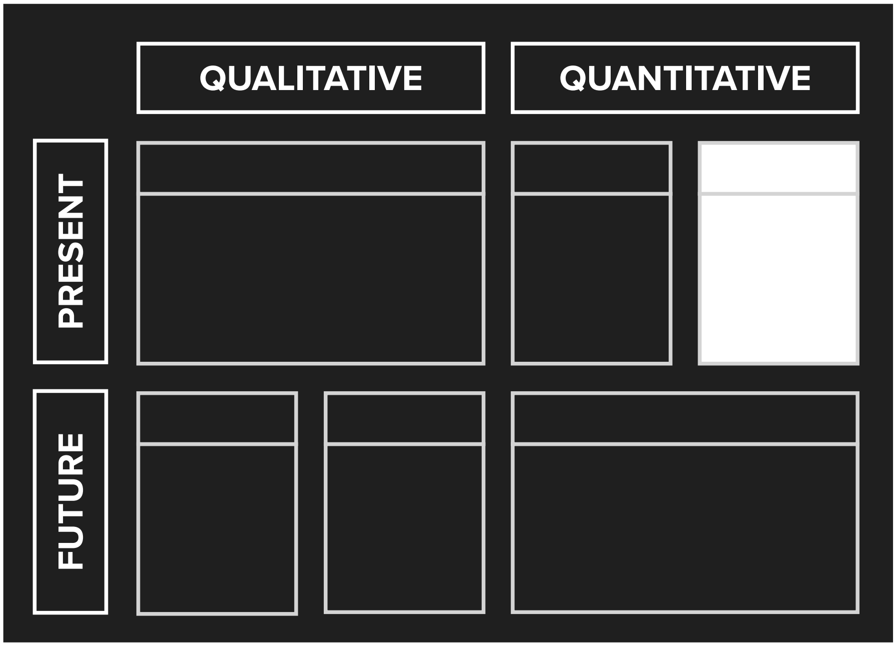
QUALITATIVE
QUANTITATIVE
PRESENT
FUTURE

5 Identifying locations and scales of today

Based on the publication:
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
Tanya Tsui, Alexis Derumigny, David Peck, Arjan van Timmeren and Alexander Wandl
Published in Frontiers in Built Environment, 8. https://www.frontiersin.org/articles/10.3389/fbuil.2022.954642

ABSTRACT In recent years, implementing a circular economy in cities has been considered by policy makers as a potential solution for achieving sustainability. Existing literature on circular cities is mainly focused on two perspectives: urban governance and urban metabolism. Both these perspectives, to some extent, miss an understanding of space. A spatial perspective is important because circular activities, such as the recycling, reuse, or storage of materials, require space and have a location. It is therefore useful to understand where circular activities are located, and how they are affected by their location and surrounding geography. This study therefore aims to understand the existing state of waste reuse activities in the Netherlands from a spatial perspective, by analyzing the degree, scale, and locations of spatial clusters of waste reuse. This was done by measuring the spatial autocorrelation of waste reuse locations using global and local Moran’s I, with waste reuse data from the national waste registry of the Netherlands. The analysis was done for 10 material types: minerals, plastic, wood and paper, fertilizer, food, machinery and electronics, metal, mixed construction materials, glass, and textile. It was found that all materials except for glass and textiles formed spatial clusters. By varying the grid cell sizes used for data aggregation, it was found that different materials had different ‘best fit’ cell sizes where spatial clustering was the strongest. The best fit cell size is ~7km for materials associated with construction and agricultural industries, and ~20-25km for plastic and metals.The best fit cell sizes indicate the average distance of companies from each other within clusters, and suggest a suitable spatial resolution at which the material can be understood. Hotspot maps were also produced for each material to show where reuse activities are most spatially concentrated.

KEYWORDS spatial clustering analysis, circular economy, urban metabolism, waste data, circular cities, Moran’s I autocorrelation, hotspot analysis

5.1 Introduction

Our current ‘take-make-waste’ or linear economy of production, where materials are extracted, used, and discarded as waste, is unsustainable. There is a pressing need to transition to more sustainable socio-technical systems that address environmental problems, such as resource depletion and excessive land use; as well as economic problems, such as supply risk and flawed incentive structures (Geissdoerfer et al. 2017). Since 2015, transitioning to a circular economy (CE) has been proposed by policy makers in the European Commission as a potential solution (European Commission 2020). In the Netherlands, companies and households produce over 43 million tonnes of waste per year, including waste materials such as food waste, packaging, iron, paper, plastics, glass, chemical waste and construction waste (Statistics Netherlands 2020). As part of its circular economy strategy, the Netherlands aims to increase waste reuse for the production of goods, in order to reduce the need to extract or import scarce raw materials, reducing pressure on the environment (Hanemaaijer et al. 2021).

Although there is no consensus on its definition (Kirchherr, Reike, and Hekkert 2017), 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 (Marin, Alaerts, and Van Acker 2020). The study of circular economy was popularized by the fields of industrial ecology, industrial design, and business management; and examined the circularity of materials, products, and companies (Bocken et al. 2016; Kalmykova, Sadagopan, and Rosado 2018; Bakker, den Hollander, and van Hinte, 2019; den Hollander, Bakker, and Hultink 2017).

Recently, there have been growing efforts to look beyond products to larger spatial scales – to buildings, cities, regions, and beyond; introducing the question of what is a suitable spatial scale at which to organize and model material flow and distribution. Much of these efforts fall under the topic of ‘circular cities’, and take the perspectives of urban governance, which studies the circularity of a city’s policies and stakeholders (Williams 2019a; Prendeville, Cherim, and Bocken 2018; Amenta et al. 2019); and urban metabolism, which studies the material, water, or energy flows of cities or regions (Dijst et al. 2018; Broto, Allen, and Rapoport 2012; Kennedy, Cuddihy, and Engel-Yan 2007).

The study of circular cities requires a spatial or geographical perspective. For cities, transitioning to a circular economy requires the introduction of circular (industrial) activities into the region, such as recycling, remanufacturing, storage, and (reverse) logistics; which are affected by spatial factors such as proximity to materials, clients, suppliers, and other companies. Because of this, scholars have started to recognize the importance of adding a geographical or spatial perspective to the study of circular cities and regions (Furlan et al. 2022; Wandl 2020; Van den Berghe and Verhagen 2021; Sprecher et al. 2021; Stephan and Athanassiadis 2017). The development of this perspective is still at an early stage, and the increasing accessibility and quality of spatial material flow data presents new possibilities. Accessible spatial material data and spatial analysis tools could provide a greatly enhanced ability to generate insights for circular economy at the regional scale. However, as more have access to these powerful tools, it is also more important to identify the limitations of spatial data analysis.

This chapter aims to add a spatial perspective to the study of circular economy by analyzing the spatial clustering of existing waste reuse activities in the Netherlands. This study answers the research question: “How does analyzing the spatial clustering and hotspots of waste reuse locations generate insights for the circular economy, and what are the limitations of these insights?” Spatial autocorrelation methods, global and local Moran’s I, were used to analyze the spatial clustering of the waste reuse locations in the Netherlands for minerals, mixed construction materials, food, fertilizer, metal, plastic, wood and paper, and machinery and electronics.

A key finding was made from varying the grid cell sizes used to aggregate the reuse location data. It was found that each material had a ‘best fit’ cell size that optimized the trade-offs between cell sizes too large and too small. Materials associated with the construction and agriculture industry (minerals, mixed construction materials, food, fertilizer) had a best fitting cell size of 7km, wood and paper of 15km, metals and plastics of ~20-25km, while machinery and electronics had no clear best fit cell size. Additionally, local spatial autocorrelation results were used to generate hotspot maps for each material, which indicated locations with a significantly high rate of waste reuse. Together, the best fit cell size and hotspot maps for each material could provide insights on which spatial scale to analyze the material, which level of governance (municipal, provincial) to write policy influencing the material, as well as other spatial attributes such as the material’s relationship to urban areas and level of centralization.

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5.2 Theoretical background

While earlier studies on CE focused on the circularity of materials, products, and companies; researchers have started exploring circularity at larger geographical scales - expanding from the product scale to neighborhoods (Codoban and Kennedy 2008), cities (Kennedy, Cuddihy, and Engel-Yan 2007), countries (Tanikawa et al. 2015), and even the entire globe (Graedel et al. 2019).

5.2.1 Space, people, and flow of circular cities (and regions)

The larger scale perspectives on material flows in a circular economy can be categorized in three perspectives, following the environmental planning framework of (Tjallingii 1996): space, people, and flows. While the following paragraphs explains these three perspectives separately, it is important to note that an integrated perspective is required for a truly meaningful understanding of circular cities and regions.

The spatial perspective, within the disciplines of urban design and planning, investigates how land use, planning, and zoning strategies affect circular activity and material flows in regions. Strategies can come in the form of developing circular infrastructure, such as adequate space for storage of materials and (circular) industrial activity, and a well functioning reverse logistics network. This could facilitate the circular flow of resources, helping to reduce the city’s intensive resource use and to tackle urban waste streams (Williams 2019b; Wandl 2020; Arciniegas et al. 2019).

The people perspective, within the urban governance context, investigates how municipalities and policy makers implement a circular economy at a city, provincial, or country level. Research from this topic involves examining policies, regulations, and strategies to understand how they facilitate, hinder, or change waste-to-resource flows; as well as listing out societal barriers for regions attempting to implement a circular economy (Prendeville, Cherim, and Bocken 2018; Amenta et al. 2019; Bolger and Doyon 2019; Van den Berghe and Vos 2019).

The flows perspective, within the field of urban metabolism, describes the flow of resources through a region be it a city, province, or country, in particular the movement and consumption of materials, energy, and water (Broto, Allen, and Rapoport 2012; Dijst et al. 2018; Kennedy, Cuddihy, and Engel-Yan 2007; Brunner 2007). It also investigates how various strategies can contribute to reducing the resource use of regions, by reducing the overall consumption of raw materials, and using industrial processes to turn waste into a resource. Our study, which analyzes the locations of waste reuse in the Netherlands, attempts to contribute to the space and flows perspective of circular regions.

5.2.2 Urban metabolism

The flows perspective on circular regions stems from the broader and more established field of urban metabolism, which studies “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and elimination of waste” (Kennedy, Cuddihy, and Engel-Yan 2007). Literature on urban metabolism began in the 1960s, with a seminal study by (Wolman 1965), in which national data on water, food, fuel use, and production rates of waste per capita was used to estimate the flow rates of a hypothetical American city of one million people.

Urban metabolism studies examine a wide variety of flows in a city or region, such as water, materials, or nutrients, in terms of mass fluxes, usually in kg or tons (Kennedy, Pincetl, and Bunje 2011). While most urban metabolism literature illustrate the input of resources and output of waste, some papers examine cyclical urban metabolism or waste metabolism, where waste produced by a region is considered as a secondary resource or input for the city. Urban metabolism studies on waste recognize that, while products are produced from resource flow pathways, waste is processed by waste treatment and recycling pathways (Zhang 2013).

In its early stages, urban metabolism treated cities and regions as a system boundary for material flow analysis, rather than a topic of study, also known as a ‘black box model’ (Song et al. 2018). The first studies in urban metabolism were accounting exercises to calculate the total input, stock, and output of water, materials, nutrients, and waste of specific cities. There was less discussion on how the spatial aspects of the city (e.g. density, land use, proximity, accessibility) affected the location of these flows. As urban metabolism developed, so did its approach to space, resulting in a variety of spatial approaches (Dijst et al. 2018). This includes mapping (geo-visualization) of stocks and flows, calculating eco-footprint of cities, incorporating insights into urban design and planning, and spatial modeling.

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Mapping of stocks includes visualization for urban mining purposes, such as construction material stock mapping (Stephan and Athanassiadis 2017; Tanikawa et al. 2015; Sprecher et al. 2021); while mapping of flows include visualization of material flows (Furlan et al. 2022; Sileryte et al. 2022), and activity based spatial material flow analysis (Dijst et al. 2018).

The study of ecological footprint of cities determines the amount of land required to provide a city with its resources and process its waste. Studies of this nature have been conducted for Vancouver, Santiago de Chile, Cardiff, and cities of the Baltic region of Europe (Kennedy, Cuddihy, and Engel-Yan 2007). The past decade has seen many more similar studies, mostly focusing on the so-called megapolis – metropolitan areas with a population exceeding ten million (Moore, Kissinger, and Rees 2013; Geng et al. 2014).

Spatial modeling (or spatial statistics, spatial econometrics) combines statistics and geometry to create statistical spatial models of material flows, allowing researchers to make predictions for future scenarios and support spatial policy decisions (Dijst et al. 2018). Urban resource demands are simulated using activity-based modeling by (Zhang 2013; Li and Kwan 2018; Keirstead and Sivakumar 2012). Other researchers have considered the interactions between an urban metabolism and the spatial distribution of land use and cover types (Zhang 2013).

5.2.3 Spatial clustering and circular regions

One potentially important aspect of geographically explicit urban metabolism is the study of spatial clustering. While there are not many spatial clustering studies on waste reuse locations, statistical tools for studying spatial clustering have been applied to many topics – from the clustering of molecules and atoms in materials studied by material scientists, to the clustering of black holes and planets studied by astrophysicists. Literature relevant to urban metabolism are studies examining spatial clustering from the perspective of waste management, urban mining, and company location.

Literature studying spatial clustering from a waste management perspective studies hot spots of waste production in order to inform waste management, recovery, and policy (Antczak 2020; Cheniti, Cheniti, and Brahamia 2021). Similar methods are also used to identify hot spot areas with high concentrations of hazardous materials in air, soil, or water; in order to minimize negative environmental impacts of pollution (Huo et al. 2012; Zhao et al. 2014; Rawlins et al. 2005).

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Literature on spatial clustering from an urban mining perspective identifies geographical clusters within a region where secondary materials (such as precious metals from e-waste, or building materials) can be extracted in the future (Zhang, Zhong, and Geng 2019; Zhu 2014). This is done through material stock analysis, such as estimating the location of construction material stocks by aggregating cadaster data, which is a comprehensive recording of real estate in a country, including information on building function, age, and height (Sprecher et al. 2021; Verhagen et al. 2021).

Literature on the spatial clustering of companies stems from a spatial econometrics perspective, which uses spatial statistical methods to verify hypotheses on theories of company location, spatial agglomeration, and economies of scale. These studies identify industry clusters in order to explain and inform regional economic development, such as infrastructure (including waste infrastructure), policy instruments, environmental laws (Malmberg and Maskell 2002; Hassan, Alenezi, and Good 2020; López and Páez 2017; Sunny and Shu 2019; Baptista and Swann 1999).

5.2.4 Research gaps

In circular economy research, the spatial study of material flows at the city or regional scale is still in its infancy. This could be because the concept of circular economy stemmed from the fields of industrial ecology, business and product design, which include the study of ‘people’, such as management and business models for circular companies; and of ‘flows’, such as secondary materials and reuse methods for circular production, but has less focus on issues related to space. Another reason could be the lack of data on material stocks and flows, as well as the all encompassing and complex nature of materials, making it difficult to define the scope of research. While other flows such as energy and transportation can be easily recorded by a centralized provider and made publicly available via census data; data on material flows is harder to collect – there is no centralized provider of ‘materials’, nor is there a straightforward way to automatically record data on material flows (Zhu 2014).

In urban metabolism research, most studies are also not spatially explicit. The majority of existing literature understands the metabolism of regions as a whole, without zooming in to examine the geographical locations of flows within the region. Of the urban metabolism studies that are spatially explicit, few studies have gone beyond geo-visualization to use spatial statistical methods (Verhagen et al. 2021). While the location of clusters or hotspots can be roughly identified by interpreting the maps visually, there is rarely spatial statistical work describing objectively how strongly materials are clustered, and where these clusters are. This could be due to the lack of detailed location data on materials, as well as the lack of accessible spatial analysis tools in the past. While spatial data on material flows may be available at the country scale through input-output tables, there is limited availability of material data at the regional, urban, or neighborhood level (Zhu 2014).

In spatial clustering research, studies have been conducted for other disciplines and topics, locating clusters of companies, pollutants, material stock, even waste production. However, the authors have not found any studies on locations of waste reuse. This is again due to lack of data. Since spatial clustering analysis has not been conducted on locations of waste reuse before, more investigation is needed for the potential insights and limitations of the spatial clustering results, especially on how (or whether) these results could provide advice for circular regional development.

Our research therefore applies existing spatial analysis methods to new data (locations of waste reuse) that were previously unavailable to researchers, in order to explore how our results could contribute to circular regional development. In terms of methodological contributions, our chapter yields new intuition on the choice of a grid size when aggregating spatial values and its consequences on spatial clustering.

5.2.5 Research aim and questions

The aim of this research is to explore how using statistical methods to analyze the spatial clustering of waste reuse in the Netherlands could provide insights for circular regional development, in order to bridge the gap between urban design and urban metabolism.

The research question is therefore: What insights and caveats can be derived from spatial clustering analysis of waste reuse locations? The sub-research questions are:

- What is the degree, scale, and location of spatial clustering of waste reuse locations in the Netherlands?
- What are the potential insights and caveats of identifying hotspot locations of waste reuse locations in the Netherlands?

5.3 Methodology

This research uses statistical methods to analyze the spatial clustering of waste reuse locations in the Netherlands. Three aspects of spatial clustering will be measured: how strongly waste reuse activities are clustered across the country, the spatial scale at which reuse activities are most strongly clustered, and the hotspots of waste reuse clusters. Global and local Moran's I, one of the most commonly used and accepted methods for analyzing spatial clustering in the fields of spatial econometrics and location science, will be used to understand the three aspects of spatial clustering mentioned above (Anselin 1995; Getis and Ord 1992).

Waste reuse data from the Dutch National Waste Registry was utilized. The data was plotted onto a map of the Netherlands as point data, then categorized by material types. For each material type, the following steps were conducted:

- The waste reuse point data was aggregated into 50 grids, with cell sizes varying from 1 to 50km.
- Global Moran's I was calculated for each of the 50 grids (cell sizes: 1-50km) to measure the degree of spatial clustering for each cell size.
- A trendline was plotted with cell size on the x-axis and degree of clustering on the y-axis, in order to identify the cell size at which clustering is the strongest.
- Local Moran's I was used to map out the hotspots of waste reuse - locations where the amount of waste reuse is significantly high.

The details of the materials and methods are further elaborated in the sub-sections below.

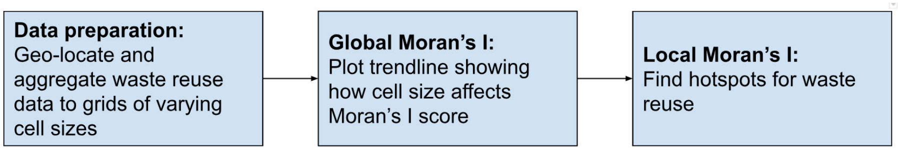

FIG. 5.1 Flowchart of materials and methods used. First, waste statistics were categorized by material type, and waste reuse addresses were geo-located and aggregated to grids of varying cell sizes, ranging from 1 - 50 km. Global Moran's I was then used to determine, for each material, the degree of spatial clustering (measured by the Moran's I score) is affected by cell size. Finally, local Moran's I was used to find hot spots of waste reuse for each material type.

5.3.1 Data preparation

This study utilized data from the Dutch National Waste Registry (Landelijk Meldpunt Afvalstoffen, LMA), which records all waste flows in the Netherlands that are processed by waste management companies, and includes information on the location of waste producers, processors, and secondary resource receivers; as well as the weight and material type of the waste produced. This study focuses on the location of 'first receivers' ('eerste afnemers' in Dutch), which are non-waste management companies that receive processed waste as a secondary resource from waste processors. The locations 'first receivers' were chosen because they most resembled locations of waste reuse. The locations of waste reuse were then aggregated onto a gridded map of the Netherlands (Figure 5.2), with each grid cell representing the sum weight of waste reused for the data points located within the cell.

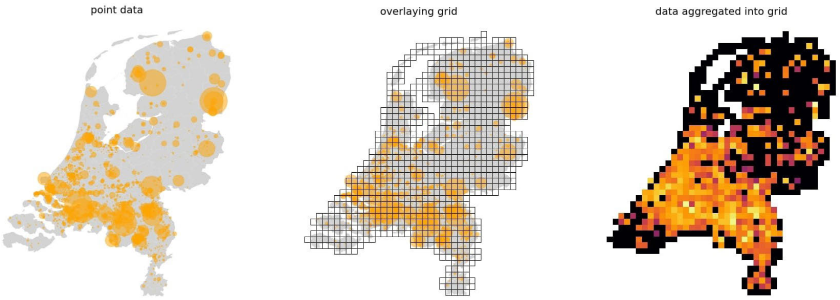

FIG. 5.2 Aggregation of point data. The locations of waste reuse is represented by point data on a map of the Netherlands. In order to aggregate the data, the following steps are taken: First, 50 grids overlapping the Netherlands were created, with cell sizes ranging from 1 to 50 km. Then, the point data for each material was aggregated for each grid. For each material type, this resulted in 50 grids with varying cell sizes, showing the amount and locations of waste reuse.

For each grid cell, the amount of waste reused was further categorized by material type. The LMA dataset represents the material type of each waste flow using either the European waste code (EWC) or the combined nomenclature code (CN). However, the categories were difficult to interpret because the categories of the two code types (EWC and GN) did not match well. In order to create more meaningful categorizations, the waste flows were re-categorized using keywords.

Finally, some flows in the LMA dataset were deemed as 'invalid' because the location of the first receiver in the dataset was either a temporary storage location, or did not represent the true location of reuse, but rather the location of the headquarters of the first receiver company. These ‘invalid’ flows were removed with consultation with waste experts from the Rijkswaterstaat (government agency for public works and water management).

5.3.2 Global Moran’s I - degree and scale of spatial clustering

Global spatial autocorrelation was used to understand the strength of spatial clustering of waste reuse locations in the Netherlands. Spatial autocorrelation is a term used to describe the presence of systematic spatial variation in a variable. A positive spatial autocorrelation of a dataset would mean that areas closer together are more similar than areas further apart. While there are multiple methods of measuring global spatial autocorrelation, this study has chosen Moran’s I (Getis and Ord 1992) as the measurement method. This is because it is one of the most commonly known spatial autocorrelation methods used in exploratory spatial data analysis, popularized by interface-based GIS (geographical information systems) tools like GeoDa and ArcGIS. This study therefore aims to focus on Moran’s I to illustrate its potentials and pitfalls, while leaving other spatial autocorrelation methods to future studies. For this study, Global Moran’s I was used to indicate the degree of spatial clustering for the materials in the LMA dataset, as well as the statistical significance of this clustering. Moran’s I values can vary from -1 to 1. A value approaching 1 indicates strong spatial clustering, -1 indicates strong spatial dispersion, and 0 indicates the absence of large clusters (Figure 5.3).

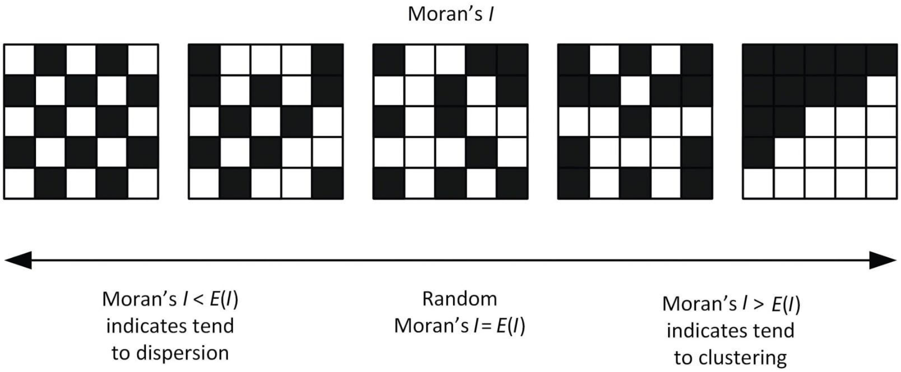

FIG. 5.3 Illustration of how map clustering affects Moran’s I score. The Moran’s I score, an indicator for spatial clustering, was used to measure the degree of spatial clustering for waste reuse. The Moran’s I score ranges from -1 to 1. A value approaching 1 indicates strong spatial clustering, -1 indicates strong spatial dispersion, and 0 indicates the absence of large clusters. Image adapted from (Kirkegaard, 2015).

The global Moran's I of a spatial random variable X is:

$$I = \frac{n}{W} \times \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} \left(X_i - \bar{X}\right)\left(X_j - \bar{X}\right)}{\sum_{i=1}^{n} \left(X_i - \bar{X}\right)^2}$$

Where *n* is the number of spatial units indexed by *i* and *j*; *x* is the variable of interest (in our case, kg of materials reused); $\bar{x}$ is the mean of *x*; W_{ij} is a queen weight matrix of spatial weights with zeroes on the diagonal, where $W_{ij} = 1$ if cells *i* and *j* share an edge or a vertice; and *W* is the sum of W_{ij}. A p-value was also calculated for the global Moran's I values for each material using a Monte Carlo method. Further explanation can be found in the supplementary materials section.

Aggregating the waste reuse data at different scales produced varying results for spatial clustering. This is a common phenomenon seen in geography, and is known as the modifiable areal unit problem (MAUP) (Openshaw 1983). The MAUP is a source of statistical bias that comes from aggregating point data into polygons. The bias takes two main forms: the scale effect, and the zone effect. Figure 5.4 below shows how the representation of point location data can be significantly changed by changing the scale (Figure 5.4, left) and zone (Figure 5.4, right) of aggregation.

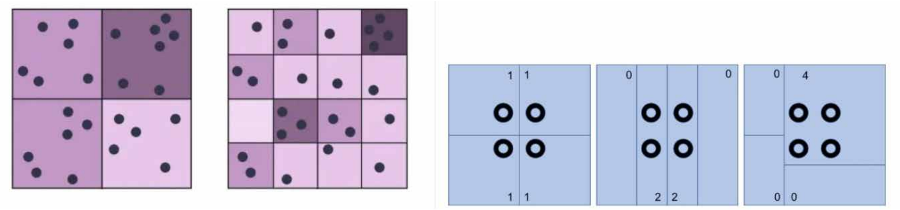

FIG. 5.4 Illustration of the modifiable areal unit problem (MAUP). The modifiable areal unit problem (MAUP), a source of statistical bias that comes from aggregating point data into polygons, takes two main forms: the scale effect, and the zone effect. The left image illustrates the scale effect, and the right image illustrates the zone effect. Images adapted from (GIS Geography, 2022).

In order to address the MAUP scale effect, each material type in the dataset was aggregated to grids of different cell sizes, from 1 - 50km. To address the zone effect, each grid was shifted randomly four times. For each grid variation (in scale and position), the Global Moran's I and p-value (of the test E(I) = 0) were calculated. The resulting 5 Moran's I values (1 original + 4 shifts) at each cell size were then plotted onto a graph with Moran's I on the y-axis and cell size on the x-axis. A LOWESS (locally weighted scatterplot smoothing) trendline was then used to estimate the cell size which results in the strongest spatial clustering, see Figure 5.5 below.

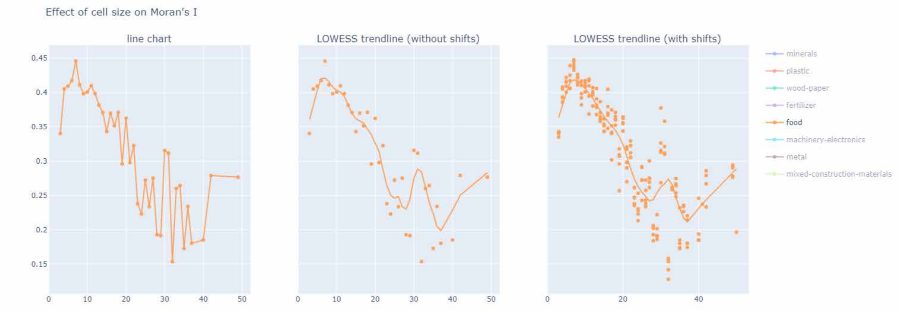

FIG. 5.5 LOWESS trendline to find cell sizes with strongest spatial clustering. For each material, point data is aggregated to 50 grids, with cell sizes ranging from 1 - 50 km. The strength of spatial clustering is calculated for each cell size, then plotted onto a chart with cell size on the x-axis and Moran's I (degree of spatial clustering) on the y-axis. The peak of the resulting trendline indicates the cell size where spatial clustering is the strongest.

The cell size which results in the strongest spatial clustering can be identified by varying the cell size for each material. This is important because spatial clustering for different materials can occur at different scales - from neighborhoods, to cities, to provinces. With this method of varying cell sizes for each material, the different spatial scales of different materials can be understood and compared.

Usually, the relatively large number cell sizes in this study would require multiple comparison corrections to account for false positives in order to establish statistical significance. However, we argue that this is irrelevant in this study. The theoretical aim of this study is to test an infinite number of cell sizes between a minimum and maximum (1-50km), whereas multiple comparison corrections account for a finite amount of hypotheses. For a more detailed explanation, refer to the supplementary materials section.

5.3.3 Local Moran's I - locations of spatial clusters

Local spatial autocorrelation (Anselin 1995) was used to identify the locations of clusters for each material type. Unlike global spatial autocorrelation, local spatial autocorrelation focuses on the relationships between each observation (each grid cell) and its neighbors, rather than providing a single-number summary for the whole map. While global Moran's I accesses the strength of clustering of a map as a whole, local Moran's I identifies the location of clusters on the map. The formula for local Moran's I is similar to its 'global' counterpart; the only difference is that, while the global Moran's I formula iterates through all pairs of polygons, the local Moran's I formula only iterates through the neighbors of one polygon. The formula for local Moran's I is shown below.

The local Moran's I of a spatial random variable X is:

$$I_i = \frac{X_i - \bar{X}}{S_i^2} \sum_{j=1,\, j \neq i}^{n} W_{ij} \left(X_j - \bar{X} \right)$$

Where X_i is an attribute for feature i, $\bar{x}$ is the mean of the corresponding attribute, W_{ij} is the spatial weight between feature i and j, and :

$$S_i^2 = \frac{\sum_{j=1,\, j \neq i}^{n} \left(X_j - \bar{X} \right)^2}{n - 1}$$

With n equating to the total number of features.

The significance of a local Moran's I value is determined in the same fashion as global Moran's I, except that the permutation is carried out for each observation in turn, resulting in a p-value for every polygon on the map (as opposed to one p-value for the whole map).

In order to identify the types of clusters, local Moran's I calculations are combined with the Moran scatter plot. This plots, for each polygon (such as a grid cell of a map), its value on the x-axis (such as kg waste reused), and the average value of its neighbors on the y-axis (also known as spatial lag). By separating the Moran's scatter plot into four quadrants and calculating each polygon's significance, we can define locations as spatial clusters of either high values surrounded by high values (hotspots) or low values surrounded by low values (cold spots); as well as spatial outliers that are low values surrounded by high values (doughnuts) or high values surrounded by low values (diamonds). Examples of Moran's scatter plots and its four quadrants are shown in Figure 5.6 below.

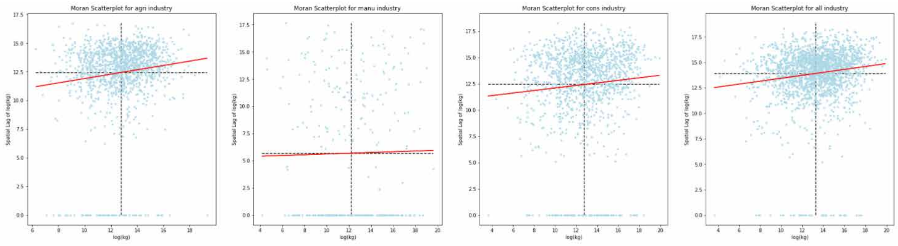

FIG. 5.6 Moran's I scatter plots for waste reuse in agriculture, manufacturing, construction, and all industries. In this scatter plot, each point represents one cell on the grid. The x-axis is the amount of waste reused in the cell, and the y-axis is the average amount of waste reused by neighboring cells. The plot can be separated into four quadrants. Hot spots, high values surrounded by high values (top right); cold spots, low values surrounded by low values (bottom left); doughnuts, low values surrounded by high values (top left); and diamonds, high values surrounded by low values (bottom right). Image adapted from (Vergara, Damgaard, and Gomez, 2016).

5.4 Results

5.4.1 Global Moran's I - degree and scale of spatial clustering

By mapping waste reuse locations on a gridded map of the Netherlands, varying the cell sizes of the grids, and calculating the global Moran's I value for each of these maps, the strength and scale of spatial clustering for waste reuse for the different material types can be identified. For each material, the Moran's I value for each cell size was compared to a random case, where the same values were used but the coordinates were randomly shuffled. The resulting charts and more detailed explanation can be found in the supplementary materials section. The resulting line charts in figures 5.7 and 5.8 show how varying cell sizes for aggregation affects the degree of spatial clustering (Moran's I) and statistical significance (p-value) of each material in the waste reuse dataset. For both plots below, the x-axis represents the cell sizes of the grid map used to aggregate the data, varying from 1 to 50 km. For Figure 5.7, the y-axis represents the global Moran's I value, while for Figure 5.8, it represents the p-value. As seen in the figures below, the majority of materials and cell sizes resulted in p-value <= 0.05, with the exception of the materials glass and textile.

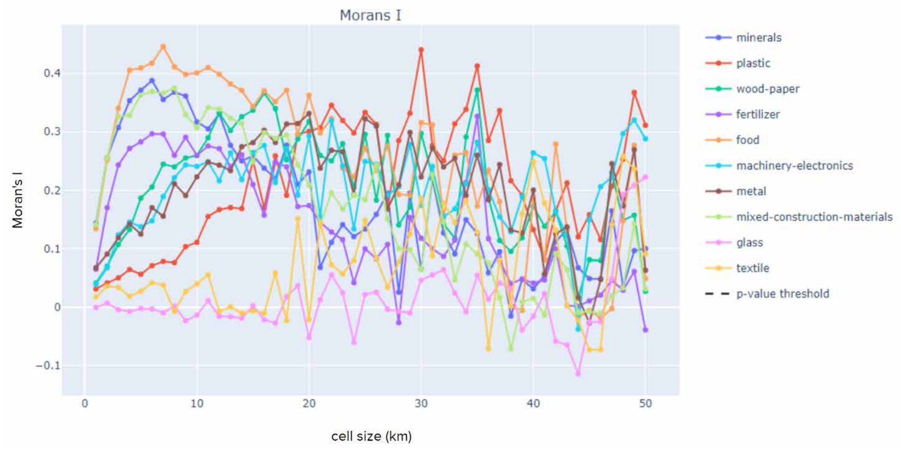

FIG. 5.7 Effect of cell size on Moran's I value. Line chart with cell size on the x-axis and Moran's I (strength of spatial clustering) on the y-axis. The chart shows, for each material, how strongly waste reuse locations are clustered at each cell size

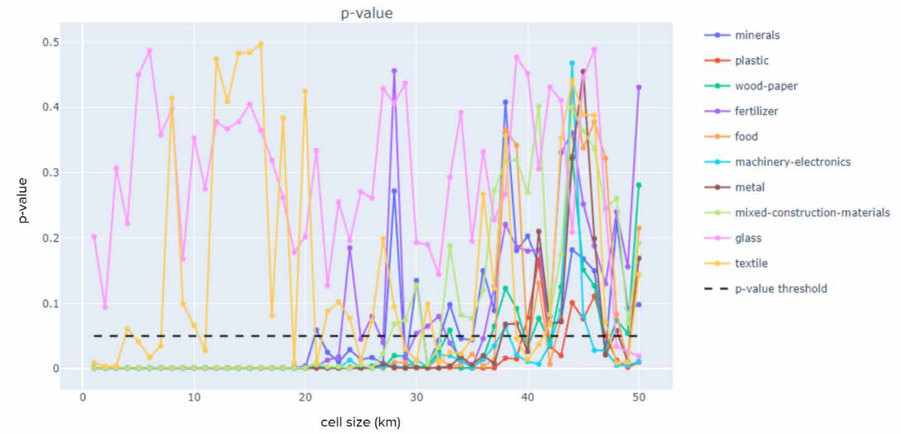

FIG. 5.8 Effect of cell size on p-value. Line chart with cell size on the x-axis and p-value (measuring statistical significance) on the y-axis. The figure shows, for each material, which cell sizes have statistically significant clustering. All materials formed statistically significant spatial clusters except for glass and textiles.

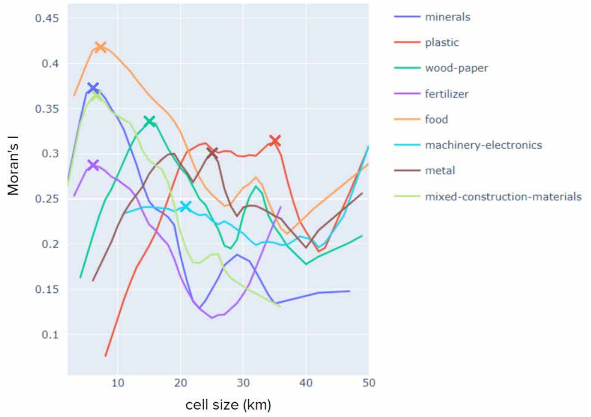

FIG. 5.9 Effect of cell size on Moran's I value. All materials are plotted onto a line chart with cell size on the x-axis and Moran's I (strength of spatial clustering) on the y-axis. Most materials have trend lines that form a peak, indicating a cell size where spatial clustering is the highest.

As seen in Figure 5.9, the trendline for most materials forms a peak, meaning that most materials have an 'best fit' aggregation cell size where spatial clustering is the most prominent. For each material in the LMA dataset, the 'best fit' cell size, as well as the global Moran's I value and p-value for that cell size, is summarized in Table 5.1 below.

TABLE 5.1 Best fit cell size, Moran's I, and total reuse in tonnes of each material

Material	Best fit cell size (km)	Moran's I	Total reuse (tonnes)
minerals	6	0.40	26,500,000
plastic	24	0.32	451,000
wood-paper	15	0.36	1,260,000
fertilizer	6	0.30	1,200,000
food	7	0.45	1,280,000
machinery-electronics	15	0.27	22,409
metal	25	0.39	1,100,000
mixed-construction-materials	7	0.37	8,420,000

5.4.2 Local Moran's I - location of spatial clusters

Once the global Moran's I and p-values have been determined for each material at each cell size, we are able to identify the locations of clusters for each material. There are four types of clusters: hot spots (red, high-high), cold spots (blue, low-low), doughnuts (light blue, low-high), and diamonds (pink, high-low). For more details on the four types, please refer to the materials and methods section. Figure 5.10 below shows, using mineral waste reuse locations as an example, the locations of clusters using the minimum cell size, the 'best fit' cell size derived from the previous global Moran's I chart (Figure 5.9 and Table 5.1), and maximum cell size. The minimum and maximum cell size is determined by the smallest or largest cell size for each material that still produced a p-value lower than 0.05 for the global Moran's I calculations (Figure 5.8). For hotspot maps for all materials in the dataset, please refer to the supplementary materials section.

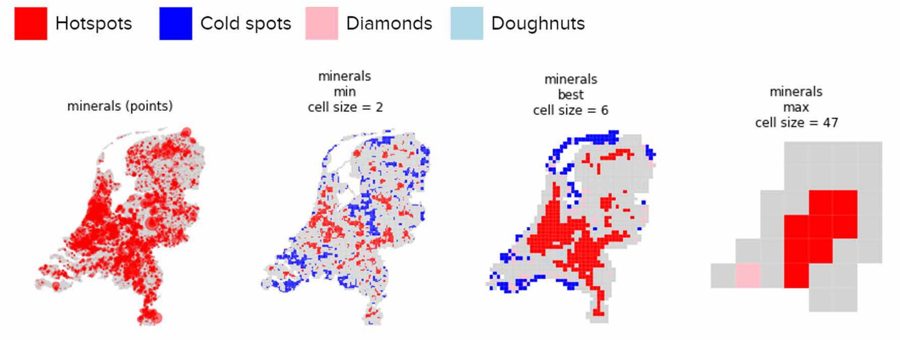

FIG. 5.10 Map of hotspots, cold spots, diamonds, and doughnuts for mineral waste reuse. Hotspot maps were created for mineral reuse at three cell sizes: smallest (2 km), "best" (6 km), and largest (47 km). The "best" cell size is the cell size where spatial clustering (measured using Moran's I) was the strongest. For hotspot maps of all material types, please refer to the supplementary materials section.

5.5 Discussion

The aim of this study was to understand the insights and caveats that can be derived from spatial clustering analysis of waste reuse locations. So far, this chapter has presented the results of global and local Moran's I analysis, on the strength, scale, and location of waste reuse clusters in the Netherlands. This section will elaborate on the insights and caveats that can be derived from these results.

5.5.1 Insights from results

The opportunities of using spatial clustering on waste reuse data to generate insights for circular regional development are presented in the paragraphs below.

In terms of global spatial autocorrelation results (global Moran's I), if a material has a high global Moran's I value and a p-value of less than 0.05, it indicates that its locations of reuse form a strong spatial pattern when displayed on a map. We can therefore conclude that the higher the Moran's I for a material, the more affected it is by geography, and the more important it is to use a spatial perspective to analyze this material. All the materials considered, except for glass and textiles, had p-values lower than 0.05, meaning there could be spatial dependence, and that spatial clusters exist. This indicates that it would be fruitful to analyze these materials from a spatial perspective.

However, it is not meaningful to compare global Moran's I values for different materials, because different materials have a 'peak' Moran's I at different cell sizes (for more explanation of cell sizes and Moran's I, please refer to the results section). This can be shown in Figure 5.11 below, where mineral reuse locations have stronger clustering from cell sizes 2-12km, while wood and paper reuse locations have stronger clustering from cell sizes 12 - 50km. As seen in the graph, an answer cannot be given on whether minerals reuse locations are more spatially clustered than wood-paper, because this depends on the cell size used for the analysis.

FIG. 5.11 Comparing spatial clustering for waste reuse locations of minerals and wood. The x-axis is cell size, and y-axis is Moran's I (strength of spatial clustering). The strength of spatial clustering for both materials vary as cell size changes. As a result, there are cell sizes where mineral waste reuse locations have stronger spatial clustering (at cell sizes 2 - 12 km), while there are other cell sizes where wood waste reuse locations have stronger spatial clustering (at cell sizes 12 - 50 km).

The effect of cell size on the global Moran's I value can be explained with Figure 5.12, where the map of mineral waste reuse is plotted as a 3D surface, with the x and y axis representing the longitude and latitude, and the z axis representing the amount (in kg) of mineral waste reuse.

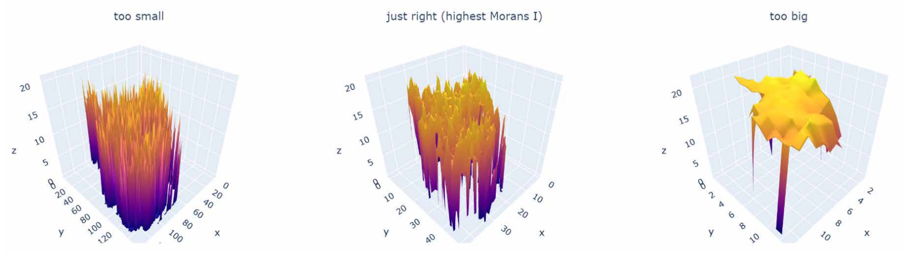

FIG. 5.12 3D plots on amount and location of mineral waste reuse. For these 3D plots, the x- and y-axis represent geographical coordinates of waste reuse locations, and z-axis represents the amount of waste reused. The three plots show waste reuse locations aggregated at different cell sizes: small (2 km), “best” (6 km), and large (47 km). For an interactive version, see the supplementary materials section.

When the cell size is too small (~ 2km), the 3D plot is highly irregular; and when the cell size is too big (~ 40km), it resembles a flat surface. For both cases, the 'resolution' of the grid is either too small or too big to form an identifiable spatial pattern. On the other hand, when plotting the cell size at which the global Moran's I value is the highest (6km), clear clusters can be identified in the form of identifiable peaks and troughs. This illustrates that the 'best fit' cell size optimizes between cell sizes that are too small (or too detailed) and too big (or too vague).

Since the highest Moran's I value for minerals occurs with 6km cell sizes, it can be stated that 6km is the resolution at which mineral reuse locations should be spatially analyzed. Explained more technically, when the locations of mineral reuse is aggregated to a grid with cell sizes of 6km, the strongest spatial pattern (clustering) can be observed. This also indicates that, within clusters of mineral waste reuse locations, most locations are, on average, 6km away from each other.

As seen in Figure 5.13 below, locations of reuse for minerals, fertilizer, food, and mixed construction materials all have a global Moran's I value that peaks at ~7km. On the other hand, the curves for plastic and metal both form an m-shape, with two peaks at different cell sizes. The first peak is similar for both materials, and happens at ~20-25km. The 'best fit' cell size for wood-paper is somewhere in between the other materials, with an 'best fit' cell size of ~15km. Finally, there was no clear 'best fit' cell size for aggregating the reuse locations of machinery and electronics.

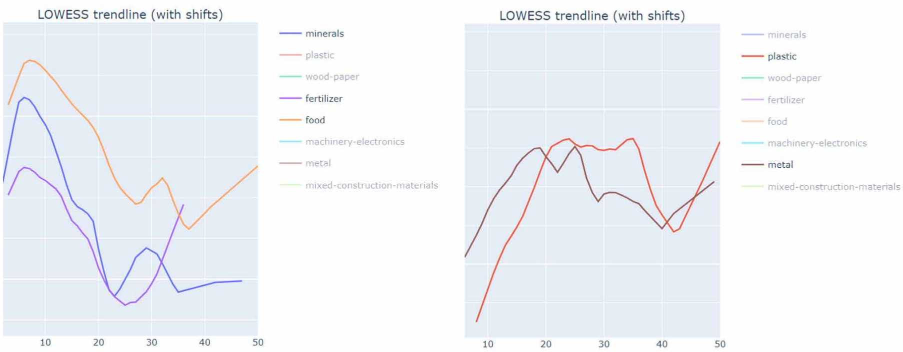

FIG. 5.13 Materials categorized according to their best fit cell size. Left figure (12a) shows materials with the best fit cell size of 7 km: minerals, fertilizer, and food. Right figure (12b) shows materials with best fit cell sizes higher than 15 km: plastic and metal.

Materials with a best fit cell size of 7km (minerals, fertilizer, food, mixed construction materials) are in the construction and agricultural industry; whereas materials with peaks of 20 - 25 km (plastic, metal) are more associated with consumer products. Arguably, the industries with smaller cell sizes (construction and agriculture) have more detailed spatial requirements than the industries with larger cell sizes (plastic and metal). Construction and agriculture are more closely related to cities - most of the activities of the construction industry happen in cities, whereas most agricultural activities happen away from cities.

Reuse of materials in the construction and agricultural industry could also be more distributed than other materials like metal or plastic. The reuse of metal would require large scale machinery at high costs, resulting in centralized locations; whereas reuse of minerals (such as concrete aggregate) can easily be done at any construction site in the country. For industries with distributed reuse locations, a reuse location could be found every few kilometers, which might explain the lower best fit cell sizes for the construction and agricultural industry. From a policy or governance perspective, the resulting spatial scales for each material might indicate the governance level at which these materials could be manipulated - from neighborhoods, to municipalities, to provinces.

We also investigated how the 'best fit' cell size of each material is affected by other attributes of the material: total kg reused for the whole country, percentage of areas with zero values, and the Moran's I value. It was found that these attributes had a weak correlation with the 'best fit' cell size, as seen in Figure 5.14 below. This indicates that the 'best fit' cell size for each material provides insights that could not have been obtained using other material attributes, suggesting that there is value in finding the 'best fit' cell size for each material.

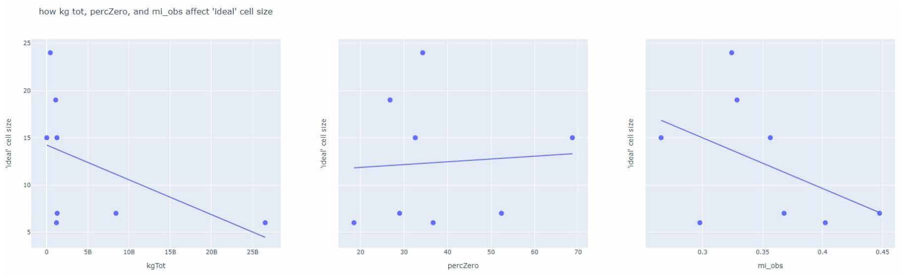

FIG. 5.14 Correlation between cell size and other factors. Plots showing correlation between best fit cell size (y-axis) and other factors: total kg of waste reused (left, kgTot), percentage of zero values (percZero, middle), and Moran's I (mi_obs, right).

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The potential insights gained from the local spatial correlation results are summarized in the paragraphs below. The results are shown as a map of hotspots, cold spots, doughnuts, and diamonds, and can be seen in Figure 5.10 in the results section.

For almost all materials, hotspots seem to be concentrated in the south of the country, roughly around the regions around Amsterdam, The Hague, Rotterdam, and Eindhoven. This is most evident in the case of machinery and electronics, where the hotspots form a clear line running along the railway line between The Hague and Roermond. The exception is fertilizer reuse hotspots, which seem to be located around the north east of the country (Figure 5.15).

Cold spots, on the other hand, indicate areas that have a significant cluster of low waste reuse. Most cold spots for most materials are located in the north-west of the Netherlands, where the Wadden islands are, as well as the south-west near the border with Belgium. The exception is food reuse locations, where cold spots are present on the north-east of the country as well. (Figure 5.15)

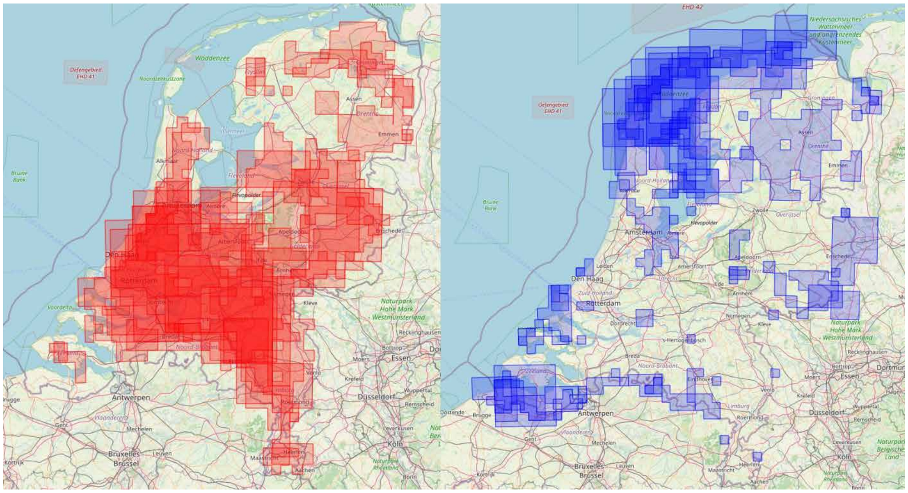

FIG. 5.15 Overlay of hotspots and cold spots for all materials. The hotspots (14a, left figure) and cold spots (14b, right figure) for all materials are overlaid onto one map.

Doughnuts indicate areas of low value surrounded by high value, whereas diamonds indicate areas of high value surrounded by low value. These location types are more distributed across the country, and don’t seem to form a distinguishable pattern.

The most evident insight from the local spatial autocorrelation maps, comes from the location of hotspots. These results can be used as a foundation for further research. Further investigation into hotspot locations using spatial regression methods can explain why hot spots are where they are. Additionally, hot spot maps can be used to imagine future (alternative) scenarios, understanding the co-location of future waste production, processing, and reuse.

Looking at the hot spot maps at different cell sizes, it becomes evident that the concept of ‘hot spot’ should be applied to an area (or region), rather than a given point on the map. In the same way that a country can be financially wealthy at the national level but may have lower-income areas at the regional or local level, one location can be said to be a hot spot for one given cell size while the same point may or may not be part of a hot spot for other cell sizes. This suggests that one point on the map plays a different role within a neighborhood, city, province, or country. This has consequences for the realization of circular cities, as different spatial scales (neighborhood / municipal / regional / national) would result in different perspectives on the hot spots, prioritizing different areas as a consequence.

5.5.2 Research limitations

The limitations of using spatial clustering methods (Global and Local Moran’s I) on waste reuse data to generate insights for circular regional development are presented in the paragraphs below.

Generally, spatial statistics require a large number of datapoints to be conducted. Therefore, for spatial statistical analysis, the phenomenon examined (in this chapter, material reuse) needs to have many locations. Just because a material has many reuse locations, however, does not mean that it should be prioritized in a circular economy. As a consequence, spatial research on circular economy neglects materials which have a large environmental impact but are only concentrated in a few locations. In this study for example, glass and textiles were eliminated from the study, even though they may have a significant impact on the environment. Moreover, this study only focused on locations of waste reuse, without taking into account other activities in the waste-to-resources supply chain - locations of material stock, waste production, and waste processing.

Limitations for this study's spatial analysis methods can be found in the interpretation of the 'best fit' cell size and local Moran's I. The 'best fit' cell size should indicate the best resolution to examine a material by optimizing the trade-off between cell sizes that are too big and too small. This can be seen in the global Moran's I results, where the 'best fit' cell size for a material is the cell size at which spatial clustering is the strongest.

Following this logic, it would be expected that the hot spot maps made with the 'best fit' cell size balances the trade-off between cell sizes that are too big or too small. When cell sizes are too small like in Figure 5.16 below, the map is precise but inaccurate. When a hotspot is indicated on this map, the reader can indicate the precise 3 by 3 km squared location that is a hotspot, but at the same time, it's more likely that this hotspot could have appeared by chance. In other words, this hotspot location might not have been statistically significant even if there had been minor changes to the material reuse rates there. On the other hand, when cell sizes are too big like in Figure 5.16 below, the map is imprecise but accurate. When a hotspot is indicated on this map, the reader can only indicate a square of 49x49 km^2 - too large to be informative, and therefore imprecise. But, at the same time, it's less likely that this hotspot could have appeared by chance.

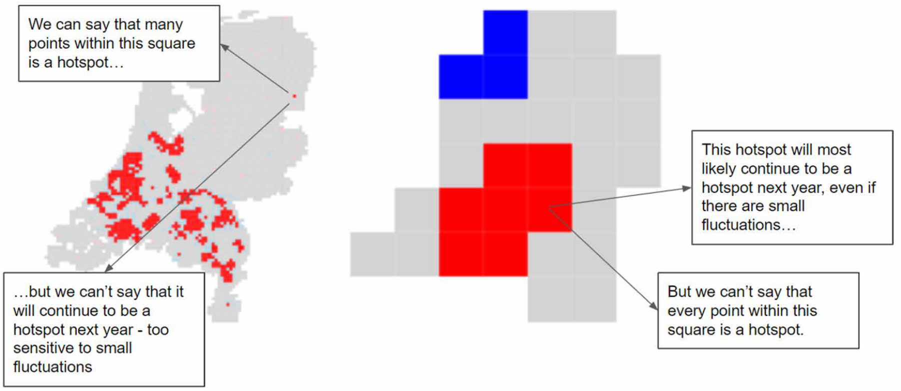

FIG. 5.16 Trade-off between large and small cell sizes for hot spot mapping. This figure shows two hotspot maps, one with small cell sizes (left), and one with large cell sizes (right). When cell sizes are too small (left), the map is precise but inaccurate. When cell sizes are too big (right), the map is accurate but imprecise.

Although it is clear in theory that a hotspot map using the 'best fit' cell size is the most informative, this is not so evident in practice. For example, when examining Figure 5.17 below, which shows the hotspot maps of food reuse locations with the minimum, 'best fit', and maximum cell size, it is tempting to say that the map with the minimum cell size is the most informative. While the minimum cell size map shows distinct areas as hotspots, the 'best fit' cell size map shows hotspots as one large area covering almost the whole south side of the country.

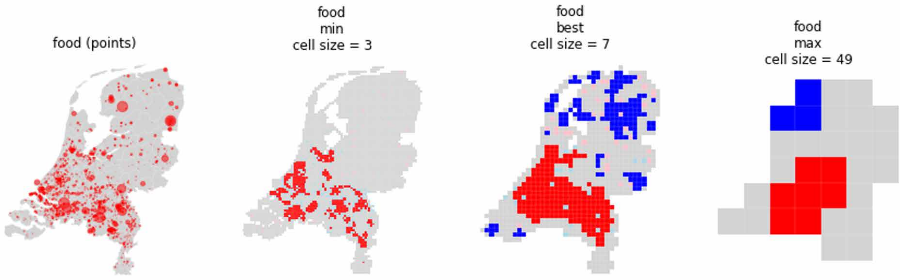

FIG. 5.17 Comparing hot spot mapping with minimum, best fit, and maximum cell sizes. Hotspot maps were created for food waste reuse at three cell sizes: smallest (3 km), "best" (7 km), and largest (49 km). The "best" cell size is the cell size where spatial clustering (measured using Moran's I) was the strongest. For hotspot maps of all material types, please refer to the supplementary materials section.

This uncertainty from choosing between the minimum or best fit cell size indicates two potential conclusions: either that the best fit cell size is not relevant for other spatial analysis methods; or that the minimum cell size map gives a false impression of accuracy and the 'best fit' cell size should be chosen. If we accept the second potential conclusion for the hotspot maps in Figure 5.17, the 'best fit' cell size map (with cell size = 7km) would provide the best possible representation of reality. Smaller cell sizes may look more precise and informative, but they are too sensitive to provide reliable information on the exact shape and number of clusters.

This indicates an important observation on spatial data analysis: while technological advancement has allowed for unprecedented precision on location data, spatial analysis results do not result in the same amount of precision. While LMA data has the precise street addresses for reuse locations, the hotspot maps created have a far lower precision, ranging from 6 to 25 kilometers depending on the material.

5.5.3 Recommendations for further research

More experimentation can be done with spatial statistical methods to identify the spatial characteristics (such as land use, density, accessibility) that affect the amount of waste reuse. In other words, this study has identified where waste reuse clusters are, the next step is to identify why the clusters are there. This can be done through spatial regression methods, which could indicate the relationship between waste reuse in a location with its associated spatial characteristics. An alternative would be to explore the same questions qualitatively, finding historical, social, or political reasons for waste reuse clusters. The factor of time could also be incorporated into the analysis, allowing a deeper understanding of how clusters change over the years. Additionally, waste material categorization can be improved to include information on re-usability. Material types can have a 're-usability score', or could be categorized as a material, component, or product. An example can be found in (Sileryte et al. 2022).

Other spatial autocorrelation methods beyond Moran's I, such as Geary's C, can be used to analyze the same dataset of waste reuse. Comparing Moran's I to other spatial autocorrelation methods would allow researchers to find out if the results of this study are merely an artifact of the Moran's I statistic.

More understanding is needed for the entire 'waste to resource supply chain'. Future studies could look beyond locations of waste reuse to examine locations of waste stock, production, and processing. A network perspective could be taken for this line of study, where aspects such centrality and travel distances could be incorporated.

More work could be done on linking spatial statistical results to policy ambitions. This would require a deeper understanding of the policy ambitions of the Netherlands and the European Union (EU), especially in terms of circular economy and spatial development. (Sileryte et al. 2022; Verhagen et al. 2021; Van den Berghe and Verhagen 2021) have made a start here, developing tools that provide information to aid policy makers in making decisions related to circular regional development.

Finally, spatial statistical methods have the potential to simulate future scenarios to determine the feasibility of current policies related to circular regional development. Future demand for materials could be matched to future supply of secondary resources (Verhagen et al. 2021). Demand and supply matching could be simulated at different scales, to determine the feasibility of 'closing the loop' at the neighborhood, city, provincial, or country level. Simulations can also be made from the perspective of disaster analysis, imagining future scenarios of extreme material scarcity, where limitations of the global supply chain could lead to substitutions with local secondary resources.

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5.6 Conclusion

In conclusion, this chapter added a spatial perspective to existing urban metabolism studies, by answering the research question, “How does analyzing the spatial clustering and hotspots of waste reuse locations generate insights for the circular economy, and what are the limitations of these insights?” The research question was answered by calculating the global and local spatial autocorrelation (global and local Moran’s I) for materials in the waste flow dataset of the national waste registry of the Netherlands.

The global Moran’s I values indicated that the reuse locations for all materials except for glass and textiles were spatially clustered in the Netherlands. The materials with spatial clustering are: minerals, mixed construction materials, wood and paper, metals, plastics, food, fertilizer, and machinery and electronics. By varying the cell sizes used to aggregate the reuse location data, it was found that each material had an ‘best fit’ cell size that optimized the trade-offs between cell sizes too large and too small. Materials associated with the construction and agriculture industry (minerals, mixed construction materials, food, fertilizer) had an ‘best fit’ cell size of 7km, wood and paper of 15km, metals and plastics of ~20-25km, but machinery and electronics had no clear ‘best fit’ cell size. Local spatial autocorrelation results were used to generate maps of hotspots, cold spots, doughnuts, and diamonds for each material.

From the results, the potential and limitations of using these results to find insights for circular regional development were identified. In terms of potential insights, the ‘best fit’ cell size identified for each material could indicate the scale or resolution at which the material could best be understood with additional spatial analysis, the potential governance level of that material (neighborhoods, cities, provinces, country), or its spatial attributes, such as its relationship to urban areas or level of centralization. The ‘best fit’ cell size is the cell size that maximizes Moran’s I and allows the researcher to display the (aggregated) map that is the most highly clustered. The hotspots maps generated from local Moran’s I values indicate which regions could facilitate reuse activities for a particular material.

On the other hand, there are also limitations to using spatial analysis results for circular economy insights. Waste data limits the focus of studies to material reuse strategies (such as recycling or incineration), while ignoring product life extension strategies (such as design or repair). Waste data is also difficult to categorize - categories that are too general, such as “metal” for example, do not provide

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sufficient information about the type of metal. Categorizations in waste dataset also often cannot match the specificity of new product material requirements. Results also lack the network or relational perspective of the whole ‘waste to resource supply chain’. More generally, spatial analysis for a circular economy may fall into the trap of over-emphasizing on materials associated with many locations, rather than a high environmental impact.

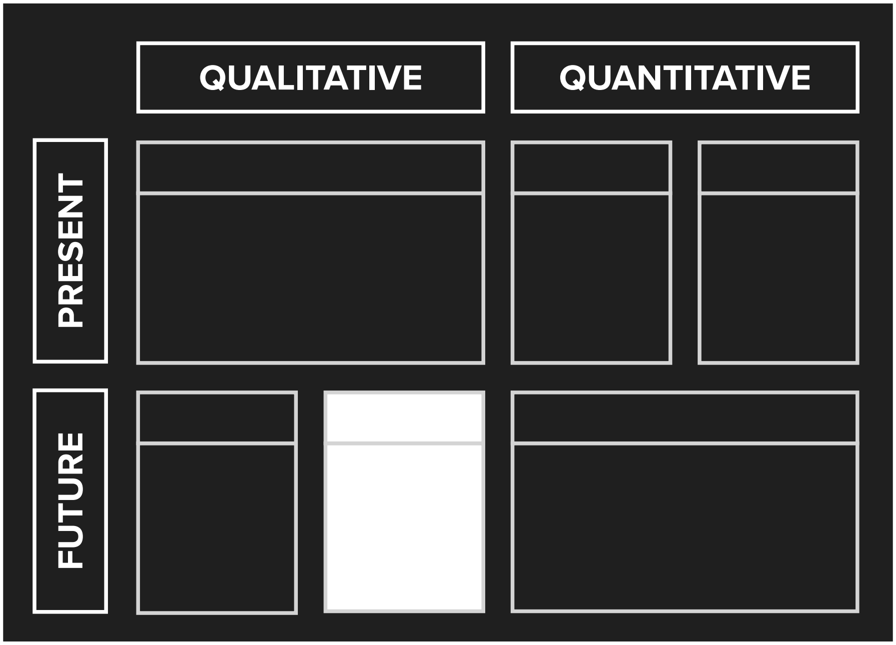
This study makes both theoretical and practical contributions to existing knowledge on urban metabolism and circular economy. In terms of theoretical contributions, we have shown an example of using spatial analysis methods to study waste reuse locations, in order to add a spatial perspective to the existing literature on regional material flows (urban metabolism) and urban governance (circular cities) for a circular economy.

The spatial perspective allows for a more detailed understanding of the locations of waste-to-resource flows by examining smaller spatial units - looking at waste reuse per neighborhood rather than per city, province, or country. Moreover, this perspective provides more objective descriptions of a material’s spatial characteristics (such as spatial clustering, scale), which goes beyond geo-visualization in the form of mapping. By varying aggregation resolutions to find an ‘best fit’ cell size, this study also contributes a potential method for addressing the modifiable areal unit problem (MAUP).

Finally, with further development, we hope that this line of research could ultimately inform spatial policy, allowing existing circular city plans of municipalities, provinces, and countries to expand their reach beyond governance and policy and towards spatial and regional planning.

Supplementary materials

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2022.954642/full#supplementary-material


QUALITATIVE
QUANTITATIVE
PRESENT
FUTURE

6 Criteria for locations and scales of tomorrow

Based on the publication:
Spatial parameters for circular hubs: criteria for future facility locations for a circular built environment in the Netherlands
Tanya Tsui, Cecilia Furlan, Alexander Wandl, Arjan van Timmeren
Published in Circular Economy and Sustainability (2023). https://doi.org/10.1007/s43615-023-00285-y

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, spatially explicit circular economy, urban mining, site selection analysis

6.1 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 (Krausmann et al., 2017). The construction sector consumes the largest share of materials globally (Levermore, 2008; Schandl et al., 2016; Urge-Vorsatz et al., 2014), and this consumption is expected to further increase in the future (Fishman et al., 2016).

Since 2015, transitioning to a circular economy (CE) has been proposed by policy makers in the European Commission as a potential solution to sustainability (European Commission, 2020). Although there is no consensus on its definition (Kirchherr et al., 2017), 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 (Marin et al., 2020).

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 (D. A. Ness & Xing, 2017). 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”) (Het ministerie van Infrastructuur en Waterstaat, 2021).

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’ (Tsui et al., 2022), and take the perspectives of urban governance, which studies the circularity of a city’s policies and stakeholders (Amenta et al., 2019; Prendeville et al., 2018; Williams, 2019); and urban metabolism, which studies the material, water, or energy flows of cities or regions (Broto et al., 2012; Dijst et al., 2018; Kennedy et al., 2007). 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 (Bahers et al., 2022; Furlan et al., 2022; Tapia et al., 2021).

Circular cities research has started to inform Dutch policy, initiating circular strategy documents at the national (Het ministerie van Infrastructuur en Waterstaat, 2021), provincial (Metabolic et al., 2019; Provincie Noord Holland, 2021; Provincie Zuid Holland, 2019), and municipal level (Gemeente Amsterdam, 2020; Gemeente Den Haag, 2018; Metabolic et al., 2018). Moreover, circular cities thinking have been implemented in spatial strategies at the national (Ministry of the Interior and Kingdom Relations, 2020), provincial (Provincie Noord Holland, 2018; Provincie Zuid Holland, 2021), and municipal level (Gemeente Amsterdam, 2021) 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.

6.2 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 (Bahers et al., 2022; Bourdin et al., 2021; Schiller et al., 2014; Tapia et al., 2021). 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 (Tapia et al., 2021).

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. (Tapia et al., 2021) identifies six territorial factors for CE: land-based, agglomeration, hard territorial factors, access to technology, knowledge-related factors, and governance; and (Bahers et al., 2022) 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 is borrowed from the study of agglomeration economies within the discipline of economic geography (Chertow et al., 2008; Desrochers, 2000).

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 (Harrison et al., 1996; Hoover, 1937; Jacobs, 1969; Porter, 1998). 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” (Mendez Alva et al., 2021), and “circular city ports” (Architecture Workroom Brussels, 2021).

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, value, as well as company diversity in the local area (Domenech et al., 2019; Jensen, 2016; Jensen et al., 2011). Some studies have also tried to define the ‘optimal’ scale for industrial symbiosis from these spatial constraints (Lyons, 2008; Lyons et al., 2009; Sterr & Ott, 2004).

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 (Sprecher et al., 2021; Tanikawa et al., 2015; Verhagen et al., 2021). 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 (Urban Agenda for the EU, 2019); building material banks, which collect, store, and re-sell building materials (Marin et al., 2020); 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 (TNO, 2018).

From literature on industrial clusters and urban mining, the concept of “circular construction hubs” can be understood in two ways: as industrial clusters, where circular companies are close to one another in order to share and exchange resources and knowledge; or as urban mining hubs, were 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 (Hodde, 2021; Mendez Alva et al., 2021; Misra et al., 2019; Tsui et al., 2022; Xue et al., 2017).

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 (Metabolic et al., 2019; Province of Gelderland, 2022; Provincie Noord Holland, 2021) and municipal level (Gemeente Amsterdam, 2020; Gemeente Den Haag, 2018; Metabolic et al., 2018).

The recent interest in circular hubs stem from the risks and limitations associated with centralized global supply chains, which were further heightened by the COVID-19 pandemic and mutating geopolitical relationships (Dumée, 2022; Wuyts et al., 2020). Manufacturing companies are rethinking their import and export strategies (Vet et al., 2021), 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 (Mendez Alva et al., 2021; Tsui et al., 2022) and material stock (Deetman et al., 2020; Sprecher et al., 2021; Stephan & Athanassiadis, 2017, 2018; Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009; van Oorschot et al., 2023). Spatially explicit studies from the industrial perspective identify existing industrial clusters for CE, but don't 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.

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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?”.

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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?”

6.3 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.

6.3.1 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 (Yin, 2015). 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 (Haezendonck & Van den Berghe, 2020), city-level circular transitions in the Netherlands (Campbell-Johnston et al., 2019), as well as circular city types in Europe (Prendeville et al., 2018).

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 (Gemeente Amsterdam, 2020; Het ministerie van Infrastructuur en Waterstaat, 2021; Provincie Zuid Holland, 2019). The Netherlands has had a circular economy strategy since 2016 (Dutch Ministry of Infrastructure and Water Management & Dutch Ministry of Economic Affairs, 2016), and circular economy concepts are integrated into the spatial development plans at the municipal and provincial scale (Gemeente Amsterdam, 2021; Provincie Noord Holland, 2018). 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.

6.3.2 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 (Gemeente Amsterdam, 2020), or more in-depth research documents such as (De Bouw Campus & Provincie Zuid Holland, 2020). 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. 17 were on circular economy strategy, and 7 were spatial development documents. Table 6.1 below shows an overview of the documents.

TABLE 6.1 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

6.3.3 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 was 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, as well as 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. Because these were semi-structured interviews, the amount of time spent on each question varied per interviewee, according to their expertise and interest. Table 6.2 below shows the list of interviewees. Please refer to the supplementary materials section for the interview questions and transcripts.

TABLE 6.2 List of interviewees.

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

6.3.4 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.

“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 (Hale & Moberg, 2003). 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 (A. van Ness, 2019). 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 (Berghauser Pont et al., 2019; D’Acci, 2019). 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, proximity to other companies (Anselin, 2010; Rosenthal & Strange, 2003).

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

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6.4 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 Figure 6.1 below.

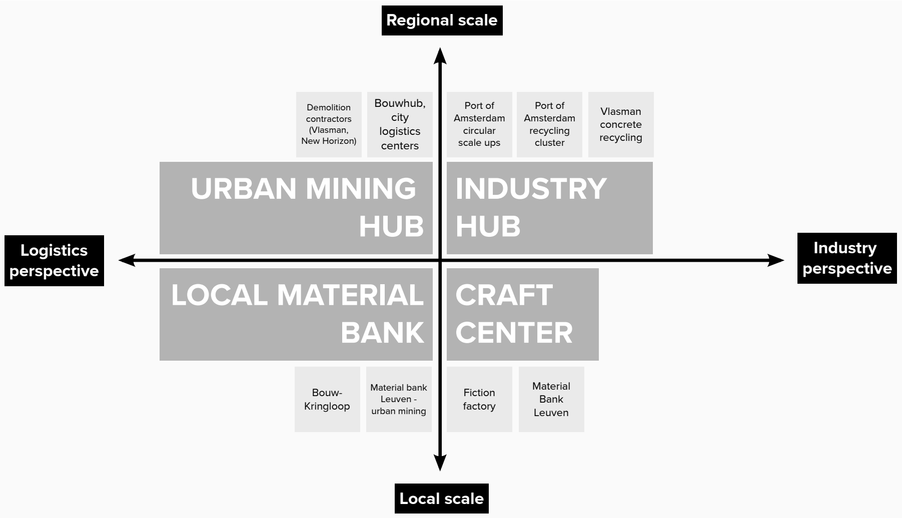

FIG. 6.1 Four types of circular construction hubs. Four types of circular construction hubs were identified during the interviews: urban mining hub, local material hub, industry hub, and craft center. The four types vary in terms of their scale (y-axis), and focus on industry or logistics (x-axis).

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 industrial sites with a high environmental zoning category (Vereniging van Nederlandse Gemeenten, 2009) 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 large space with high ceilings (1200-1500 sqm) is required for storage of materials. People with a distance from the labor market are often employed for operations.

Table 6.3 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 can be found in the supplementary materials section.

TABLE 6.3 Summary of spatial parameters for four types of circular construction hubs. For the full list, please refer to the supplementary excel sheet (see supplementary materials for full table).

	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 (10-20km). Road is the main type of transportation, Water transportation doesn't make sense because flows are not large / consistent enough	Buildings of 1200-1500 sqm with loading and unloading areas needed. Exemptions are often made for craft centers. They don't fit into industrial land because they have social activities like workshops, and they don't 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 50-100km. 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.	10-30ha, 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, 10-20km. Typically road transportation is used. Water transportation is interesting for scaling up.	1200-1500 sqm. 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,
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 30-50km. 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 5-10ha, 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.

6.4.1 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 materials section.

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 (Randazzo et al., 2018; Rikalovic et al., 2014). Spatial clustering analyzes the degree of clustering of points distributed in space, and allows for the identification of hotspots (Aldstadt, 2010; Tsui et al., 2022). Facility location analysis identifies the optimal placement of facilities to minimize transportation costs (Melo et al., 2009).

6.4.1.1 Industry hubs

For “resources” parameters, industry hubs process bulk construction materials such as asphalt, concrete, sand, gravel (De Bouw Campus & Provincie Zuid Holland, 2020; Interviewee F, personal communication, June 21, 2022), and top-soil (Interviewee C, personal communication, June 10, 2022). These 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 (TNO & Provincie Zuid Holland, 2022).

For accessibility parameters, the suggested scale for industry hubs vary - some sources suggest there is potential to expand to the whole of western Europe (Interviewee A, personal communication, May 30, 2022), 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 (De Bouw Campus & Provincie Zuid Holland, 2020). However, the transportation distance limit for asphalt and concrete is around 50-100 km (De Bouw Campus & Provincie Zuid Holland, 2020; Interviewee K, personal communication, July 22, 2022).
While the road network is currently used (Interviewee F, personal communication, June 21, 2022), there is interest in using waterways (Architecture Workroom Brussels, 2021; Interviewee A, personal communication, May 30, 2022; Ministry of

the Interior and Kingdom Relations, 2020) of class III or higher (De Bouw Campus & Provincie Zuid Holland, 2020) 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 (Provincie Noord Holland, 2018). Larger plots of 10-30 ha are needed (De Bouw Campus & Provincie Zuid Holland, 2020), and should have an environmental category of 4.1 or higher to avoid nuisance (De Bouw Campus & Provincie Zuid Holland, 2020; Provincie Zuid Holland, 2021; TNO & Provincie Zuid Holland, 2022). 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 (Ministry of the Interior and Kingdom Relations, 2020).

For socio-economic parameters, a strong local ecosystem is needed, consisting of innovative circular industry and supply chains (Interviewee A, personal communication, May 30, 2022), construction related companies (Gemeente Amsterdam, 2020; Provincie Zuid Holland, 2019), and existing recycling capacity (De Bouw Campus & Provincie Zuid Holland, 2020; Interviewee A, personal communication, May 30, 2022), in order to form circular clusters (Provincie Noord Holland, 2021; Provincie Zuid Holland, 2019), and share energy, space, materials, and knowledge (Gemeente Amsterdam, 2020; Interviewee A, personal communication, May 30, 2022; Provincie Noord Holland, 2021; Provincie Zuid Holland, 2019).

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 materials. Find industrial estates with an environmental category of 4.1 - 4.2, with plots of at least 10-30 hectares. Then, find hotspots of bulk construction waste recyclers with spatial clustering methods such as local Moran's I (Tsui et al., 2022) or DBSCAN (Mendez Alva et al., 2021). 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 50km 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 are estimated. Secondly, the future supply of top-soil can be found in data on future construction sites that overlap with greenfields.

6.4.1.2 Urban mining hubs

For resources parameters, urban mining hubs deal with building materials and products that don't need processing before redistribution (TNO & Provincie Zuid Holland, 2022). This can include building elements (e.g. bricks) or products (e.g. doors) (Interviewee F, personal communication, June 21, 2022; Interviewee K, personal communication, July 22, 2022), greenery (Interviewee C, personal communication, June 10, 2022; Interviewee I, personal communication, June 24, 2022), 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, personal communication, June 24, 2022; Interviewee K, personal communication, July 22, 2022). Government buildings are backed by the governmental circular public procurement strategies, which allow for more centralized coordination of construction and demolition (Province of Gelderland, 2022; Provincie Utrecht, 2021).

For accessibility parameters, interviewed hubs state that they are currently serving clients within their own city, meaning the operations scale is around 30-50km (Interviewee A, personal communication, May 30, 2022; Interviewee C, personal communication, June 10, 2022; Interviewee F, personal communication, June 21, 2022; Interviewee I, personal communication, June 24, 2022). The road network is usually used because it's more efficient and reliable than waterways (Interviewee B, personal communication, June 3, 2022; Interviewee F, personal communication, June 21, 2022; Interviewee I, personal communication, June 24, 2022; TNO & Provincie Zuid Holland, 2022). There is interest in using waterways or railways to reduce environmental impact, but flows are not large enough to make this financially feasible (Architecture Workroom Brussels, 2021; Interviewee A, personal communication, May 30, 2022; Interviewee C, personal communication, June 10, 2022; Interviewee K, personal communication, July 22, 2022).

For land use parameters, existing ports, industrial estates, or business parks can be used (Metabolic et al., 2018; Provincie Noord Holland, 2021; Provincie Utrecht, 2021), with plots that range from 1-10ha, with an environmental category of at least 2 (Architecture Workroom Brussels, 2021; Interviewee I, personal communication, June 24, 2022; TNO & Provincie Zuid Holland, 2022). Large plots are required because building materials are bulky, fragile, and difficult to stack (Interviewee B, personal communication, June 3, 2022; Interviewee C, personal communication, June 10, 2022).

For socio-economic parameters, urban mining hubs could be made by expanding existing construction logistics hubs (TNO & Provincie Zuid Holland, 2022), 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, personal communication, June 10, 2022; Interviewee F, personal communication, June 21, 2022; Interviewee I, personal communication, June 24, 2022).

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 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 (Tsui et al., 2022) or DBSCAN (Mendez Alva et al., 2021), 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 50km 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.

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6.4.1.3 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, personal communication, June 10, 2022; Interviewee J, personal communication, July 7, 2022). 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, personal communication, June 10, 2022; Interviewee J, personal communication, July 7, 2022).

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, personal communication, June 10, 2022; Interviewee G, personal communication, June 21, 2022; Interviewee J, personal communication, July 7, 2022).

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, personal communication, June 10, 2022; Interviewee J, personal communication, July 7, 2022).

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, personal communication, June 10, 2022; Interviewee G, personal communication, June 21, 2022; Interviewee J, personal communication, July 7, 2022).

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 minute 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 square meters in size. Prioritize older buildings, as they will more likely be abandoned. Then, find

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hotspots of hardware stores and thrift shops with local Moran's I (Tsui et al., 2022) or DBSCAN (Mendez Alva et al., 2021), 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.

6.4.1.4 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 (Hale & Moberg, 2003). 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).

6.5 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; Interviewee F; Interviewee 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 don't need a hub, a storage location is still needed by construction material dealers and recyclers, who could also be located on circular hubs.

6.5.1 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.

6.5.2 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, then by nearby building material resellers (Interviewee C, personal communication, June 10, 2022; Interviewee F, personal communication, June 21, 2022; Interviewee K, personal communication, July 22, 2022). 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 (TNO & Provincie Zuid Holland, 2022). 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 (Campbell & O’Kelly, 2012).

While most interviewees have provided an approximate service area of their hub (e.g. “our partners are generally within a 30km 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 (Tong & Murray, 2012) to balance between these two opposing factors to find a suitable service area of a circular hub (Hodde, 2021; Interviewee E, personal communication, 2022; Interviewee K, personal communication, July 22, 2022).

6.6 Conclusion

In conclusion, this chapter 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 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.

6.6.1 Limitations

While this study provides spatial parameters for circular hubs, the locations of hubs don't 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.

6.6.2 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.

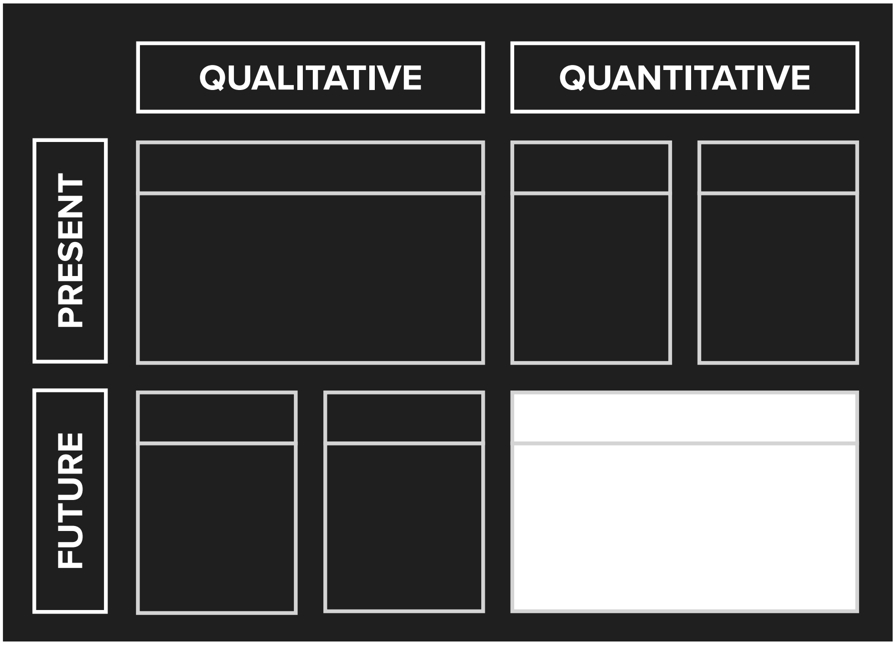
A dataset could be developed to identify the amount of building products and elements in different building types. While urban mining datasets already estimate the amount of materials per building type, the next step is to create an ontology that connects building types to building products and elements. 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 materials

Supplementary materials for this article can be found in the following link:
https://link.springer.com/article/10.1007/s43615-023-00285-y#Sec20


QUALITATIVE
QUANTITATIVE
PRESENT
FUTURE

7 Identifying locations and scales of tomorrow

Based on the publication (currently being peer reviewed):
Spatial optimization of circular timber hubs
Tanya Tsui, Fabio Duarte, Titus Venverloo, Tom Benson
Preprint available at https://assets.researchsquare.com/files/rs-3013682/v1_covered_8c6bcd55-52ea-4be3-b28c-4c243fcbb818.pdf?c=1686725490

ABSTRACT Construction is responsible for 38% of CO2 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 chapter, 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.

KEYWORDS Circular economy, circular cities, circular construction hubs, GIS, spatial optimization, simulated annealing

7.1 Introduction

Cities consume 60–80% of natural resources globally, produce around 50% of global waste and 75% of greenhouse gas emissions (Hoballah et al., 2012). 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 (United Nations, 2017). 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 (European Commission, 2020). 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 (Kirchherr et al., 2017).

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 because these elements play a large role in the success of a CE (Bahers et al., 2022; Bourdin et al., 2021; Schiller et al., 2014; Tapia et al., 2021).

Researchers agree that no single spatial scale is most suitable for closing material loops. Instead, literature shows cases of successful waste-to-resource exchanges at multiple scales, from local, to regional, to global (Chertow, 2000; Domenech et al., 2019). 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 (Chertow, 2008; Lambert & Boons, 2002) or even the same facility (Mulrow et al., 2017) exchange resources such as electricity, heat, and organic waste. At the regional scale, with resource exchange distances of around 30 - 50 km (Jensen et al., 2011; Sterr & Ott, 2004), surveys have found cases of companies collecting, re-processing, and re-selling waste as secondary materials within the same region, as recyclable material needs to be sorted and aggregated locally in order to ensure profitability (Lyons, 2008; Lyons et al., 2009). Finally, studies have also found the validity of closing material loops at the global scale. Surveys have found that, for recycling and waste treatment companies, closing resource loops globally is the norm (Lyons, 2008; Lyons et al., 2009), and that a fully circular economy for some materials is only possible at the global scale (Graedel et al., 2019). These various scales of material loops illustrate the significance of proximity and resource exchange distances in developing a CE.

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The spatial scale of closing material loops is determined by a number of factors, including the value, weight, and reusability of a resource (Chertow, 2008; Jensen, 2016; Jensen et al., 2011; Sterr & Ott, 2004); as well as operational concerns such as transportation costs and profit margins (Lyons, 2005, 2008; Lyons et al., 2009). Literature discussing the spatial scales of closing material loops have studied existing waste management facilities, which are not functioning within a fully circular economy (Lyons, 2008; Lyons et al., 2009; Graedel et al., 2019). A mathematical optimization approach, combined with data on the future demand and supply of circular materials, can give insight on the workings of a fully circular system in the future.

7.1.1 Circular construction hubs for timber in the Amsterdam Metropolitan Area

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 2,500 square kilometers, consists of 30 municipalities, with a population of 2.5 million inhabitants. The municipality of Amsterdam currently has ambitious goals for transitioning to a CE, aiming to use 50% less raw materials by 2030 (City of Amsterdam & Circle Economy, 2020). The MRA has also signed a green deal on timber construction, which aims for 20% of new construction in the city to be made of timber by 2025 (Metropool Regio Amsterdam, 2021). Timber is well suited for reuse in circular construction, as it is light and easy to manipulate, making it well suited for dry, detachable connections (van der Lugt, 2021).

In the Netherlands, construction and demolition companies have responded to policy goals for a more circular built environment by starting circular construction hubs: facilities that collect, store, process, and redistribute construction waste to be reused as secondary construction materials (TNO & Provincie Zuid Holland, 2022; Tsui et al., 2023).

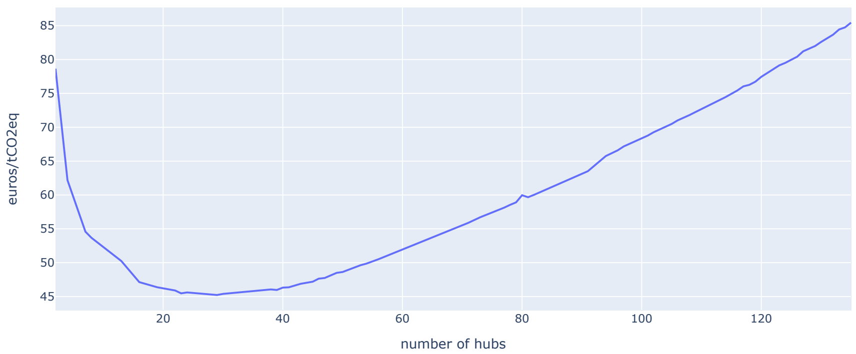
The goal of this chapter is to determine what spatial scale circular construction hubs should be operating at. On one hand, small-scale hubs minimize transportation distances due to smaller service areas. On the other hand, large-scale hubs maximize supply and demand matching—the larger the service area of a hub, the more likely there will be a match between a demolition site supplying secondary material and a construction site demanding it (Tsui et al., 2023).

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 tCO2eq reduction, was used in our algorithm to determine the optimal solution. The candidate hub locations were industrial sites in the study area with an environmental zoning category (Vereniging van Nederlandse Gemeenten, 2009) of 2-3, which are industrial sites 30-100 km from quiet residential areas, and 0-50 km from mixed areas (Interprovinciaal Overleg (Provincie), 2022). The locations of future supply and demand for secondary timber were extracted from a scenario study of material stocks and flows of construction materials in the Netherlands (van Oorschot et al., 2023). 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 Methods.

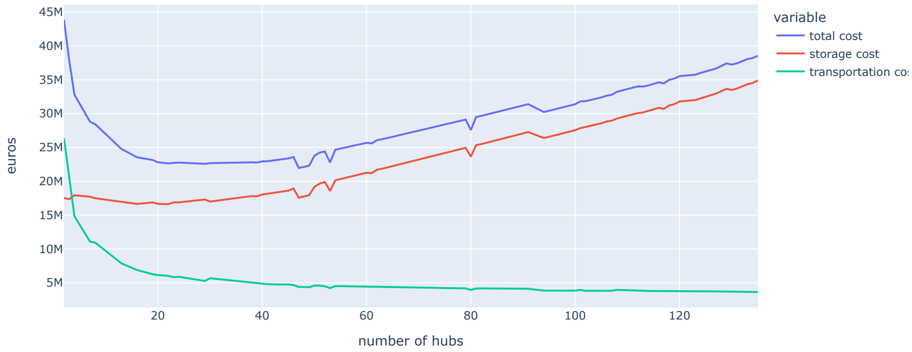
7.2 Results

Using the spatial simulated annealing optimization, the cost per tCO2eq 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 tCO2eq reduction curve, where the x-axis represents the number of hubs, and the y-axis represents the cost per tCO2eq reduction (Figure 7.1). We found that placing 29 hubs in the study area resulted in the lowest cost, although the value remains consistently low for 20 to 40 hubs, at around 45-46 euros / tCO2eq 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 CO2eq reduction of 499 kilo tons, which is 94.6% of the maximum tCO2eq reduction possible for the MRA.

(A) Cost per tCO2 reduction



(B) Total costs



(C) Total emissions reduction

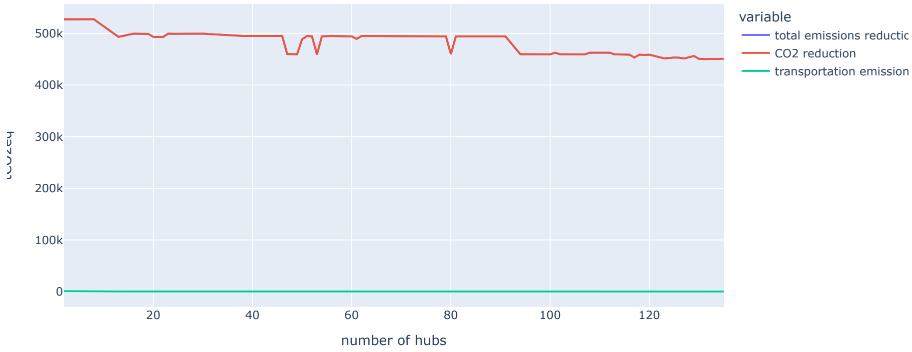


FIG. 7.1 Summary of results. Line charts showing changes in (A) cost per tCO2 reduction, (B) total costs, and (C) total emissions reductions as number of hubs increases. For chart C, the line for “total emissions reduction” (in blue) is hidden behind the line for “CO2 reduction” (in red), because the two values are very similar.

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 (Figure 7.2). 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.

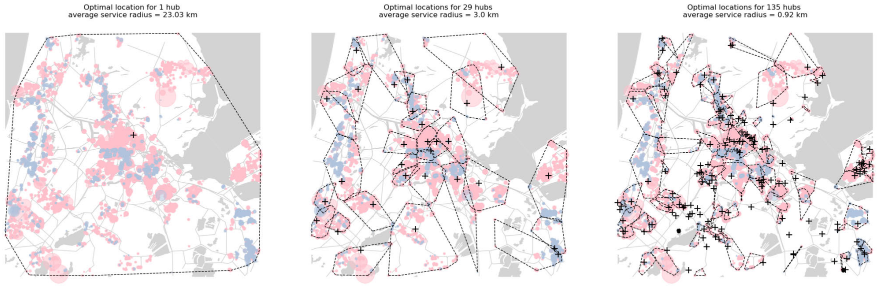


FIG. 7.2 Optimal locations and service areas for 1, 29, and 135 hubs. Black crosses = hub locations, black dotted lines = service areas, blue dots = timber supply, pink dots = timber demand, gray lines = road network.

For each industrial site, we counted how many times it was chosen as an optimal location, and found that some industrial sites were more frequently chosen than others (Figure 7.3). These locations are potential key future locations for circular timber hubs. Given the fact that the Dutch government (or any other organization) is unable to control the exact number of timber hubs built, 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 Figure 7.3). These locations are therefore less important for the creation of circular timber hubs, and could be prioritized for other functions.

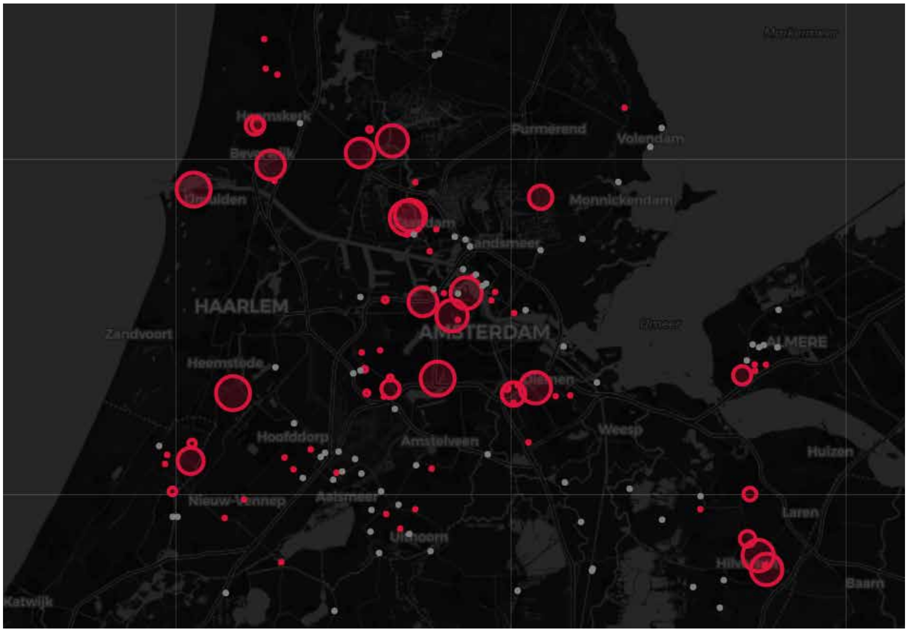


FIG. 7.3 Popularity of candidate hub locations. Circle size represents the number of times the location has been chosen as an optimal location. Red dots are locations that were chosen at least once, gray dots are locations that were never chosen.

7.3 Discussion

The cost per tCO2eq 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 (Figure 7.1). When the number of hubs is lower (nHubs = 2 - 20), cost / tCO2eq reduction decreases 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/tCO2eq remains roughly constant because all the components (transportation cost and emissions, storage cost, and CO2eq reductions) remain roughly the same when more hubs are added. When the number of hubs goes above ~40, cost/tCO2eq 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 (Figure 7.4).

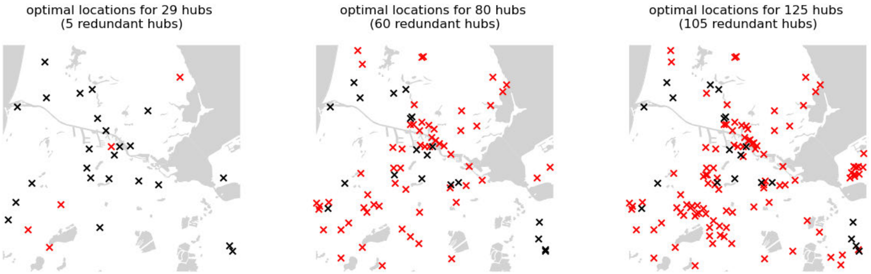


FIG. 7.4 Redundant hubs for solutions with 30, 80, and 125 hubs. Black crosses = functioning hubs, red crosses = redundant hubs, gray dots = supply and demand locations

Each of the four components of the cost/tCO2eq 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.

CO2eq emission reductions do not have a large effect on the curve – adding more hubs doesn't make a significant difference in reducing CO2eq emissions. While there is a slight decrease in CO2eq 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 the future timber supply is only around 350,000 tons. This excess demand guarantees that most of 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 CO2eq reduction from timber reuse.

7.3.1 Limitations

This study has a number of limitations, and shows the difficulty of making spatial planning decisions solely based on statistical methods. The results of this study should not directly lead to policy decisions, but should rather be seen as insights informing policy makers.

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 in the future based on future needs (supply and demand locations). This study is also limited to the MRA. 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.

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 don't communicate or share resources with each other. In reality, there are various 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. These variations, aligned with management studies, were not a research topic in this chapter.

For the calculation of cost / tCO2eq reduction, a number of assumptions were made based on existing studies on circular construction hubs (TNO & Provincie Zuid Holland, 2022; Tsui et al., Forthcoming). Changing these assumptions could have an impact on the results. This is especially true for the calculation of storage costs and tCO2eq reduction, as these parameters are based on more assumptions than transportation costs and emissions. For more details please refer to the methods section.

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7.3.2 Theoretical and practical contributions

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 (van Oorschot et al., 2023). 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 this study, it is 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 (all located on industrial sites) in the MRA, as well as industrial sites that should be prioritized as locations of timber storage and exchange. It also illustrates an 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 guide policy decisions by providing insight that cannot be obtained by the individual companies alone.

7.4 Methods

We aimed to identify the optimal spatial scale for circular timber hubs in the MRA using a mathematical optimization method called 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

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value. The number of hubs with the lowest cost effectiveness value was determined as the optimal number of hubs. The diagram below (Figure 7.5) summarizes the overall methodology.

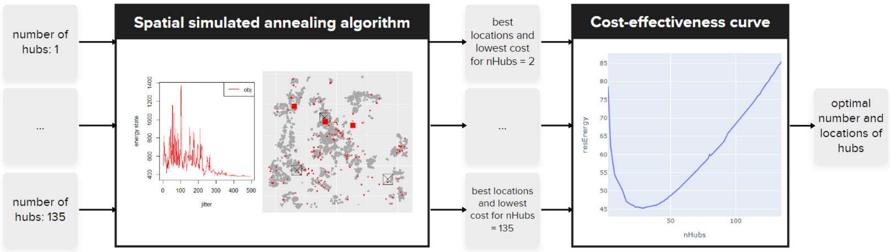

FIG. 7.5 Diagram showing overall methodology. We iterated through a range of hubs from 1 to 135 and found the best hub locations for each iteration. The cost-effectiveness of the best locations for each iteration was plotted on a cost-effectiveness curve. The lowest point of the curve indicated the optimal number of circular timber hubs for the MRA.

7.4.1 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 (Tong & Murray, 2012). Given the 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 (Ingber, 1993; Kirkpatrick et al., 1983). 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.

7.4.2 Optimization objective: cost effectiveness

The objective of the algorithm, represented below by equation (1), is to choose a combination of hub locations that are most cost effective – that minimizes costs and maximizes CO2eq emission reductions through timber reuse.

$$C_{eff} = \frac{C_{stor} + C_{trans}}{R_{CO2eq} - E_{trans}} \tag{1}$$

Where:
C_{eff} = cost effectiveness (euros / tCO2eq reduction)
C_{stor} = storage cost (euros)
C_{trans} = transportation cost (euros)
R_{CO2eq} = CO2eq reduction from timber reuse (tCO2eq)
E_{trans} = transportation emissions (tCO2eq)

Cost-effectiveness is an indicator used in sustainability research that compares the costs and benefits of different sustainable interventions (Arimura et al., 2012; Berndes & Hansson, 2007). 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 / tCO2eq reduction value. The number of hubs with the lowest cost effectiveness value was determined as the optimal number of hubs.

7.4.3 Cost-effectiveness: contributing factors

The factors contributing to cost effectiveness - storage cost, transportation cost, CO2eq reduction, and transportation emissions, are explained below. For more details see the supplementary information document and programming scripts (Tsui, 2023/2023).

7.4.3.1 Storage cost

The calculation of storage cost is expressed in equation (2). To calculate the storage area, we assumed that the average storage time of timber is six months (Tsui et al., Forthcoming), 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 (Statistics Netherlands, 2023). The rental price, which varies at each location, was based on governmental data on industrial sites in the Netherlands (Interprovinciaal Overleg (Provincie), 2022).

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

Where:
C_{stor} = storage cost (euros)
a_{stor} = storage area (sqm)
p_{build} = building price per square meter (euros / sqm)
p_{rent} = rental price per square meter (euros / sqm)

7.4.3.2 Transportation cost

The calculation of transportation cost is expressed below in equation (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 (Rijkswaterstaat, 2016).

$$C_{trans} = p_{trans} \times \sum_{i=1}^{n} d_{SH} \times t_S + d_{HD} \times t_D \tag{3}$$

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

7.4.3.3 Transportation emissions

Transportation emissions were calculated using a similar method as transportation costs, expressed below in equation (4). The emissions associated with transporting timber were based on a life cycle analysis for road transportation in Europe (Spielmann et al., 2007).

$$E_{trans} = e_{trans} \times \sum_{i=1}^{n} d_{SH} \times t_S + d_{HD} \times t_D \tag{4}$$

Where:
E_{trans} = transportation emissions (tCO2eq)
e_{trans} = transportation emissions associated with transporting 1 ton of timber for 1 km (tCO2eq)
d_{SH} = transportation distance from supply location (S) to hub location (H)
t_s = tons of timber at a specific supply location (S)
d_{HD} = transportation distance from hub location (H) to demand location (D)
t_D = tons of timber at a specific demand location (D)

7.4.3.4 CO2eq reduction

The CO2eq reduction from timber reuse is expressed below in equation (5). The value is the amount of CO2eq 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 CO2eq emissions for this scenario are emissions associated with incinerating excess waste timber that was not reused.

$$E_{CO2eq} = \sum_{i=1}^{n} e \times m_p - e \times m_s \tag{5}$$

Where:
E_{CO2eq} = CO2eq reduction from timber reuse (tCO2eq)
e = tCO2eq emissions associated with incinerating one ton of timber (tCO2eq)
m_p = amount of waste timber to be incinerated if no timber was reused (tons)
m_s = amount of waste timber to be incinerated if there is timber reuse (tons)

7.4.4 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 (Vereniging van Nederlandse Gemeenten, 2009) of 2-3. These conditions were chosen based on existing research findings on the spatial requirements for circular hubs in the Netherlands (TNO & Provincie Zuid Holland, 2022; Tsui et al., 2023). Industrial sites' locations, environmental categories, and rental prices were obtained from a governmental dataset (Interprovinciaal Overleg (Provincie), 2022).

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 x 100m (van Oorschot et al., 2023). 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 (City of Amsterdam & Circle Economy, 2020).

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 (Samuel-Rosa, 2019). 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 ((DHPC), 2022). The programming scripts can be found in the supplementary materials section.

Supplementary materials

Data and code for spatial optimization and calculating cost effectiveness are available at: https://github.com/TanyaTsui/spatialOptimizationCircularHubs

8 Conclusions and recommendations

The past five chapters of this thesis have explored different approaches in determining locations and scales of closing material loops in a circular economy. A variety of qualitative and quantitative methods were tested, based on a range of research disciplines – from industrial ecology to economic geography. Based on the research findings, this chapter answers the main research question by identifying 5 tensions in determining the locations and scales of closing material loops. It also reflects on the research methods and provides recommendations for further research.

8.1 What determines the locations and scales of closing material loops in a circular economy?

This dissertation defines a circular economy (CE) as a paradigm that aims at 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. In the Netherlands, CE concepts have been integrated into governmental policy in the form of a national circular economy strategy (Dutch Ministry of Infrastructure and Water Management & Dutch Ministry of Economic Affairs, 2016).

In earlier development stages, CE research did not explicitly take into account spatial perspectives, focusing instead on the circularity of materials, products, and companies. However, as CE gained a wider audience, circularity was explored at larger geographical scales, applying circular strategies to neighborhoods, cities, and regions; which resulted in the beginning of a spatially explicit perspective on CE. This can be seen in academic literature on circular cities and regions, which takes an

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urban governance perspective to understand how municipalities and policy makers implement circular strategies at the city or regional level; or an urban metabolism perspective to quantify the flows of materials and waste in a city or region. Circular city concepts have also been integrated into Dutch policy documents, both in circular economy and spatial strategies (Campbell-Johnston et al., 2019; City of Amsterdam & Circle Economy, 2020; Gemeente Den Haag, 2018; Metabolic et al., 2018, Dutch Ministry of the Interior and Kingdom Relations, 2020; Gemeente Amsterdam, 2021; Provincie Noord Holland, 2018; Provincie Zuid Holland, 2021)

However, despite the recent interest in circular cities, research providing a spatial perspective on the topic is still in its infancy, especially at the beginning of this research project in 2019. This is especially the case for determining locations and scales of closing material loops. At the same time, other disciplines have already developed a number of spatial analysis methods that could be relevant to the study of CE. Economic geography and spatial econometrics research provide a theoretical foundation and statistical methods to determine and explain the locations of economic industrial clusters. Industrial ecology research provides methods and datasets for mapping the locations of material stocks and flows, as well as factors that affect the distance of waste-to-resource exchanges.

The goal of this thesis was therefore to deepen our spatial understanding of the circular economy by borrowing spatial approaches from different disciplines to determine more optimal locations and scales for closing material loops. To achieve this goal this dissertation had three aims: To enhance our spatial understanding of CE by developing a theoretical framework to determine locations and scales of closing material loops; to understand the current spatial state of CE by finding locations and scales for closing material loops today, and to develop spatial recommendations for CE by proposing locations and scales for closing material loops in the future.

The main research question, **“what determines the locations and scales of closing material loops in a circular economy?”**, was answered in five chapters. The following sections provide, for each of the five chapters, a summary of the sub-research questions, methodology, and research results. Together, the chapters answer the main research question using both qualitative and quantitative approaches, as well as present- and future-oriented perspectives. The research scope progresses from general to specific, with earlier chapters analysing 10 material types in the whole country of the Netherlands, and later chapters focusing on construction materials in the city of Amsterdam and its surrounding region.

8.1.1 Chapter 3: Conceptualizing locations and scales in a circular economy

Chapter 3 provided a theoretical foundation for understanding locations and scales for closing material loops by identifying the drivers, barriers, and limitations of circular urban manufacturing - processes that produce goods using local secondary resources. Using qualitative methods (literature review and expert interviews) and taking both and present and future oriented perspectives, two research questions were answered:

- **Does urban manufacturing contribute to a circular economy in cities, and if so, how?**
- **What are the drivers and barriers to circular urban manufacturing?**

It was found that, while urban manufacturing does indeed contribute to a circular economy, there were a number of caveats to closing material loops at a local scale – transportation emissions generally play a minor role in the total emissions of producing a product, and the local scale is not necessarily the best scale for closing material loops. In fact, localizing production can even lead to a negative environmental impact - smaller processes cannot take advantage of economies of scale.

Drivers and barriers to circular urban manufacturing were identified from three perspectives: space, people, and flow. From the spatial perspective, the presence of circular urban manufacturing depends on the availability of affordable industrial land and manufacturing spaces. From the people's perspective, circular urban manufacturers were located in areas with a higher availability of skilled labor, local customers, and business support networks. From the flow perspective, circular urban manufacturing was driven by the availability of municipal and industrial waste in urban areas. Industries related to construction, fashion, bio-based products, and electronics were identified as suitable for an urban location, as well as products that were of small and high value (e.g. jewellery), design-driven (e.g. custom-made products), have short life-times (e.g. food), or were essential goods (e.g. face masks during the COVID-19 pandemic).

8.1.2 Chapter 4: Spatial factors for scales and locations of today

Using quantitative methods and a present-oriented perspective, chapter 4 answered two research questions:

- **Does the location of waste reuse follow a spatial pattern?**
- **What is the correlation between the amount of secondary resources received by waste re-users in the construction industry, and the space, people, and flow-related factors?**

The statistical significance of spatial patterns were identified using global Moran's I. To identify relevant correlations, the space, people, and flow factors from chapter 3 were translated into quantitative spatial factors that could affect the location of waste reuse. Then, the Pearson's correlation coefficient was used to find relationships between the spatial factors and waste reuse locations.

It was found that two industrial sectors (construction and agriculture) and seven materials formed strong spatial patterns. Categorizing flows according to material rather than industry led to more spatial clustering. This suggests that companies using similar materials (e.g. wood, steel, cement) tend to cluster together regardless of what industry they are in (e.g. manufacturing, construction); whereas companies in similar industries (e.g. manufacturing, construction) do not cluster together regardless of what materials they use (wood, steel, cement). Thus, the spatial patterns in the Netherlands seemed to be driven more by material than by industry.

Correlations were found for flow and space-related factors, but not for people-related factors. This suggests that actors within the waste-to-resource supply chain tend to attract each other and cluster together to form agglomerations, and that locations of waste reuse are not related to attributes of the local population, such as local income, skills, or education.

8.1.3 Chapter 5: Identifying locations and scales of today

Using quantitative methods and a present-oriented perspective, chapter 5 provided a spatial econometric approach to identifying industrial clusters for closing material loops, and answered two research questions:

- **What is the degree, scale, and location of spatial clustering of waste reuse locations in the Netherlands?**
- **What are the potential insights and caveats of identifying hotspot locations of waste reuse locations in the Netherlands?**

The location and scale of waste reuse clusters in the Netherlands were identified using spatial statistical methods. Spatial auto-correlation, a statistical method used to quantitatively measure spatial clustering and identify statistically significant spatial hot spots, was used to analyse the reuse of 10 waste material types, using data from the National Waste Registry of the Netherlands.

It was found that all the studied materials except for glass and textiles formed statistically significant spatial clusters. To determine the scale of spatial clustering, the grid cell sizes for data aggregation were varied, to find the cell size that had the strongest spatial clustering. The so called "best fit cell size" is ~7 km for materials associated with construction and agricultural industries, and ~20–25 km for plastic and metals. The "best fit cell size", or scale of spatial clustering of waste reuse, could be related to the material's associated industry, giving some indication on the level of centralization required. They also suggest a suitable spatial resolution at which the material can be further analysed using spatial analysis. The locations of statistically significant clusters, or hot spots, were identified. It was found that, for almost all materials, hot spots seem to be concentrated around the major cities - Amsterdam, The Hague, Rotterdam, and Eindhoven.

8.1.4 Chapter 6: Criteria for locations and scales of tomorrow

Using qualitative methods and a future-oriented perspective, chapter 6 provided a spatial planning approach to determining the criteria for future locations and scales of closing material loops. Two research questions were answered:

- **What are the spatial parameters for locating circular construction hubs in the Netherlands?**
- **What are the spatial data and analysis methods required to identify the potential locations of circular construction hubs in the Netherlands?**

Spatial parameters were identified for circular construction hubs - facilities that close material loops by collecting, storing, and redistributing demolition waste as secondary construction materials. Using the Netherlands as a case study, parameters were extracted from two sources: Dutch governmental policy documents, and interviews with companies operating circular hubs. The parameters were then translated into a list of spatial analysis methods that could be used to identify potential future hub locations.

Four types of circular construction hubs were identified: (i) urban mining hubs, (ii) industry hubs, (iii) local material banks, and (iv) craft centers. Urban mining hubs (i) are for sorting, storing, and distributing building components and products. Circular industry hubs (ii) house large scale and industrial circular activity, and process bulk construction materials such as asphalt and concrete. Local material banks (iii) collect, store, and re-sell residue flows ignored by larger companies. Circular craft centers (iv) use residue construction flows to make smaller scale products, such as furniture or retail spaces.

The parameters were then translated into a list of spatial analysis methods required to identify future locations of these four types of circular construction hubs - site selection, spatial clustering, and facility location. Site selection analysis selects the best location or site for a hub based on spatial criteria such as proximity to amenities, availability of materials, or accessibility. Spatial clustering analyzes the degree of clustering of points distributed in space, and allows for the identification of hot spots of secondary materials. Facility location analysis identifies the optimal placement of hubs to minimize transportation costs.

8.1.5 Chapter 7: Identifying locations and scales of tomorrow

Using quantitative methods and a future-oriented perspective, chapter 7 provided a industrial ecology and logistics approach to identifying future locations and scales, and answered the following research question:

- **What is the optimal scale and locations for circular timber hubs in the Metropolitan Region of Amsterdam?**

A spatial simulated annealing algorithm was used to identify the optimal scale and location for circular timber hubs in Amsterdam and its surrounding region. The optimal scale was defined as a scale that is most cost effective, minimizing costs and maximizing emissions reductions through timber reuse.

The optimal number of hubs for the study area was 29, with an average service radius of 3 km. When compared to other options, the optimal number and locations of hubs allowed for a total cost reduction of 21.3 million euros and a total CO2eq reduction of 499 kilo tons, which is 94.6% of the maximum tCO2eq reduction possible for the study area. The cost effectiveness was affected mostly by transportation and storage costs. When hub numbers were low (at ~2-20), adding more hubs rapidly decreased transportation costs. When hub numbers were higher than ~40, adding more hubs increased storage costs due to redundancy. Transportation emissions and emissions reductions for timber reuse had minimal effect on cost effectiveness. Future demand for timber was much higher than future supply, allowing almost all timber waste to be reused, regardless of hub scale. As a recommendation for future spatial development, a map was made for key industrial sites which were repeatedly chosen by the algorithm as optimal locations.

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8.2 Five tensions

What determines the locations and scales of closing material loops in a circular economy? Like the answer to many research questions, this dissertation's answer is, "it depends" – on which discipline you're working from, on who is asking the question, and on how you define the concepts of "locations and scales" and "closing material loops". The chapters summarized in the paragraphs above illustrate the diversity of theoretical perspectives and methods that could be applied to circular economy research to determine the locations and scales for closing material loops. Because they originate from different disciplines, these perspectives do not always align.

Five tensions have been identified as a result of the diverse spatial perspectives of this research. The tensions can be divided into two groups: conceptual and methodological. Conceptual tensions (tensions 1 and 2) result from different definitions of closing of material loops. Methodological tensions (tensions 3, 4, and 5) come from contrasting methodological decisions for spatial analysis, which correspond to different theoretical perspectives on space and circular economy.

The word "tensions" is used here to illustrate how spatial approaches to a circular economy can point towards different directions, both conceptually and methodologically. This is not to say that the concepts cannot be resolved, or are necessarily incompatible with each other. Rather, these concepts are categories that can be seen as complementary opposites, with the strengths of one perspective compensating the limitations of another – examples include masculine and feminine, yin and yang, or grapes and cheese.

Each tension answers the main research question by showing opposing definitions and approaches in determining locations and scales for closing material loops. The following sub-sections provide an explanation for each tension, by defining the characteristics of the opposing concepts, explaining the theoretical foundation, associated methods, and limitations of each concept, and, when appropriate, providing recommendations for combining the complementary opposites.

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8.2.1 Tension 1: Urban manufacturing and urban mining

Closing material loops in a CE can be seen in two ways in existing literature: urban manufacturing and urban mining. Urban manufacturing closes material loops by producing new products using locally sourced secondary (waste) materials. It is ‘production’ oriented, and the study of urban manufacturing borrows from academic fields that study manufacturing and industry location, such as economic geography and business management. It is ‘urban’ to take advantage of labor, skills, technology, and consumer base available to cities. From this perspective, location explanations are mostly socio-economic, and related to agglomeration benefits of large densities of people and companies. Scale (or scaling up) is a major barrier for this perspective. The high cost of land and insistence on the local supply chain prevents the scaling up of urban manufacturing activities. A paradox was identified in urban manufacturing literature – if urban manufacturers want to stay local, they must stay small, reducing their potential impact on the city. If they scale up and try to grow their business, their positive impact may increase, but they often leave the city completely.

Urban mining, on the other hand, closes material loops by surveying material stocks and develops solutions to gather and redistribute these materials as secondary resources. It is ‘sourcing’ or ‘end of life’ oriented, and the perspective originates from material stock and flow analysis studies from industrial ecology; as well as facility location studies in waste management. It is ‘urban’ because cities have a high concentration of secondary materials in the form of building stock. The locations and availability of materials are mapped using kadaster data – spatial data on the age, function, and size of buildings. Scale is addressed from a material flow analysis perspective, which understands that while materials by be concentrated in cities, material exchanges are often at larger distances due to business and technical constraints (Jensen, 2016; Sterr and Ott, 2004; Graedel et al., 2019) Urban mining literature has developed a significant amount of high resolution spatial data on the availability of secondary materials, which allows for large scale spatial analysis of strategies of closing material loops.

From this research, it seems that the urban mining perspective is more suited for quantitative spatial analysis for CE. There is more spatial data available, the amount of material studied is much larger, and stakeholders (such as circular hubs, governmental bodies) seem to be more interested in recommendations that result from the research conducted from this perspective. This could be because urban mining directly addresses secondary materials at a large scale by mapping material availability in urban building stock, whereas the impact of urban manufacturing on CE is less direct and tangible. Urban manufacturing literature prioritizes on justifying why industry needs to return to the city, and how changes in spatial planning and land use regulations can aid this. While this is an important research direction, it is not necessarily directly relevant to a CE (Croxford et al., 2020; Fedeli et al., 2020).

There are opportunities in connecting urban mining with urban manufacturing. One example could be locating urban manufacturing facilities based on urban mining data, similar to the research in chapters 6 and 7 on circular hubs. This would require close collaboration with a manufacturer interested in reusing waste, and translating their business and material requirements into spatial parameters.

8.2.2 Tension 2: Clusters and hubs

The key locations for closing material loops can be conceptualized in two ways: clusters and hubs. The two perspectives are based on two disciplines, are associated with different economical and business models, and result in different research methods.

From the clusters perspective, material loops are closed when companies are close together and exchange resources. Often, a diverse range of materials are exchanged between companies from different industries. Much of this perspective can be found in industrial symbiosis literature, which is based on agglomeration theory in economic geography. Locations for closing material loops are seen as (industrial) clusters or hot spots, and scale is addressed by measuring distances of material exchange, what affects these distances, as well as the spatial resolution of clusters. The associated methods for this perspective are spatial auto-correlation to find location and resolution of clusters, and spatial regression to find factors that explain the cluster locations (see chapters 4 and 5).

From the hubs perspective, material loops are closed by facilities that collect, process, and redistribute secondary materials, often processing a single material from a single industry. The perspective is associated with literature on logistics, industrial ecology, and waste management. Site selection analysis using pre-defined parameters can be used to find suitable hub locations, and spatial optimization can be used to find the optimal scale and locations of hubs.

The two perspectives have different suitability for identifying locations and scales for closing material loops. The clusters perspective is suitable for identifying locations, but less so for scale. An attempt was made to address scale by finding the spatial resolution of waste reuse clusters that resulted in the strongest spatial clustering. While resolution suggests the average distance between companies within clusters, it does not give answers to the scale of material loops. The hubs perspective is capable of providing definitive answers for both the questions of locations and scale. However, associated spatial analysis methods, site selection and spatial optimization, require assumptions to be made by the researcher, which leads to higher uncertainty.

The two perspectives also lead to different treatment of spatial parameters in the research process. From the clusters perspective, spatial parameters are the end point of an analysis. Locations of clusters are statistically analyzed to find which spatial parameters these locations are associated with. From the hubs perspective, spatial parameters are the starting point. The parameters are defined by the researcher, and then used as criteria for site selection, or constraints for spatial optimization.

Research results from the two perspectives also appeal to different stakeholders. ‘Clusters’ research can be used from a top-down perspective, by governments or large organizations like a port authority, to choose or develop locations that are attractive to circular companies. ‘Hubs’ research can be used from both a top-down and bottom-up perspective. Individual companies such as circular hubs can use it to select a suitable location, and governments can use it to understand the collective impact of a network of hubs as a whole.

As explained above, “clusters” and “hubs” are distinct concepts derived from different theoretical foundations. However, the two terms are often used interchangeably within CE research and policy documents. In any given region, both approaches will likely be approached in tandem, depending on the interests of stakeholders involved.

8.2.3 Tension 3: Spaces, people, and materials

The factors that affect locations and scales of closing material loops can be understood from three perspectives: space, people, and materials. This ties into what data is collected, what policy recommendations are made, and who is responsible for implementing strategies.

The spatial perspective refers to how availability and attributes of land (usually industrial land) affect the closing of material loops. It concerns data on locations of industrial land and their attributes, such as accessibility and environmental category permissions, as well as land use requirements for circular hubs and clusters. The people perspective explains the locations of closing material loops by analyzing company location data, such as the locations of material waste producers, processors or re-users; and population census data, such as population density, skills, income. The materials perspective examines how the location of material stock affects the location and scale of circular hubs and clusters. This is done by finding hot spots of material stock, or finding locations that maximize accessibility to the future supply and demand of materials. Scale is most clearly determined with this perspective, either from material-related constraints from companies, such as a limited travel distance for collecting materials; or through spatial optimization, by matching future supply and demand of materials within a specific geographical area.

Each perspective has a number of limitations and corresponding research gaps. For the spatial perspective, there is a danger of over-prioritizing industrial land for CE activity, when there could be more urgent needs such as housing, health, recreation, or biodiversity. Further research is needed to prioritize industrial land in accordance with multiple agendas, to ensure that spatial strategies for CE do not interfere with other goals.

For the people perspective, population attributes, such as population density, income, and skills, are not relevant to large-scale circular activities. While there is no doubt that large-scale CE activities have a clear impact on incomes, skills, and jobs in an economy, our research has found that they have very little impact on these factors within the local area. Instead, these population attributes are important to smaller scale activities such as circular maker spaces, craft centers, or local material banks. There is currently a research gap in using quantitative spatial analysis methods to identify spatial parameters required for these activities, as well as suitable locations.

For the materials perspective, current material stock analysis studies are disproportionately prioritizing the mapping of bulk construction materials, even if reusing these materials doesn't lead to the highest environmental impact. More research is needed to decide on which materials to prioritize according to their environmental impact, as well as developing methods to estimate the locations of these material stocks. While there is ample information on the locations of future material supply from material stock analysis, there is very little research on future material demand. Data in future material demand locations is essential for determining spatial scale, as this allows for the optimization of supply and demand matching.

Recommendations for circular cities and regions requires the incorporation of all three perspectives, with each perspective leading to different roles of stakeholders in facilitating the closing of material loops. From the spatial perspective, governments are responsible for determining which industrial sites to prioritize for a circular economy. An example of this can be seen in studies conducted by the province of South Holland (van Merrienboer et al., 2022; De Bouw Campus and Province Zuid-Holland, 2020). In the Netherlands, this prioritization of land seems to be most suitable at the provincial scale, as they contain a large enough number of industrial sites, and have an influence on land use permissions.

From the people perspective, larger organizations can set up circular clusters based on the co-location of related companies, in desirable locations. Examples can be found in the development of circular clusters in port regions in the Netherlands and Flanders (Architecture Workroom Brussels, 2021; Gravagnuolo et al., 2019; Haezendonck & Van den Berghe, 2020). However, spatial statistical analysis methods presented in this research are insufficient for this perspective. The success of circular industrial clusters depends more on non-spatial factors such as connections between companies, funding, or organizational structures; rather than spatial factors such as proximity to other companies (ch. 6). Although it is possible to identify locations of clusters and explain why they are there, it is difficult to provide implementable advice to specific stakeholders with this information.

From the materials perspective, material loop closing facilities such as circular hubs can use spatial analysis to choose locations that maximize their access to materials. Governments can use spatial optimization to estimate the rough number and locations of hubs required to strike a balance between storage costs, transportation emissions, supply and demand matching.

8.2.4 Tension 4: Present and future

This dissertation used two approaches to time: analyzing the present with empirical data, and making recommendations for the future based on scenarios. The two approaches are supported by opposing philosophical stances - descriptive and normative (Maxwell and Loomis, 2010; Creswell, 1994; Guba and Lincoln, 1989), and have complementary strengths and weaknesses when it comes to providing recommendations for the future development of CE.

In this dissertation, the chapters using **present-oriented approaches are descriptive**, describing or explaining phenomena as they are observed without making value judgments. In other words, we are describing what the world is, rather than what the world should be. Descriptive methods allow for objective and unbiased observations, and are based on empirical evidence and data. This can be seen in chapters 4 and 5, where the locations and degree of spatial clustering of waste reuse was objectively described using spatial econometric methods. The spatial auto-correlation analysis allowed for a measurable comparison between different waste materials in terms of their spatial clustering.

However, descriptive methods have two important limitations. Firstly, while stakeholders often have a strong preference for using empirical data and statistical methods to make decisions, descriptive methods do not directly lead to recommendations for action or decision-making. This is because examining data on existing phenomena limits our perspective on the present and the past, neglecting potential major paradigm shifts and black swan events, and thus providing limited guidance on what to do in the future. When providing future recommendations based on present data, we run the risk locking in to existing patterns. This can be seen in chapters 4 and 5, which used waste reuse locations to identify clusters of CE activity, even though there are mismatches between the ontology of waste statistics and CE monitoring (Sileryte, 2023). Secondly, descriptive methods are limited by data availability and accuracy. In chapter 5, preliminary results led to a focus on waste reuse locations that were spatially statistically significant, which excluded two materials - glass and textiles. Chapter 7, on the other hand, focused on the construction industry due to the availability of spatial data on building material stock, as opposed to other materials.

In this dissertation, the chapters using **future-oriented approaches are normative**, making judgments based on a particular set of values, principles, or norms. In other words, we are describing how the world should be, rather than how the world is. Normative methods provide an aspirational vision, imagining ideal or preferred future states, potentially providing clear recommendations for decision-making. This allows for the exploration of future paradigms or scenarios that don't yet exist, that diverge far from the present. This can be seen in chapters 3, 6, and 7. Chapter 3 explored the future paradigm of circular urban manufacturing, driven by various political, economic, technological, and cultural forces. Chapter 6 explored the potential future of establishing networks of circular construction hubs as infrastructure in the CE transition. Chapter 7 recommended the optimal locations and scales of circular construction hubs in Amsterdam using spatial optimization methods.

However, normative methods are subjective by nature, reflecting the values and perspectives of a limited number of individuals, at a given point in time, based on biased assumptions and agendas. This can be seen throughout all chapters, which is biased towards the view that CE is a major solution for environmental sustainability. More specific examples can be found in chapter 3, which assumes that circular urban manufacturing using locally available secondary material reduces carbon emissions; and chapters 6 and 7, which assumes that circular construction hubs are key to the CE transition.

There are opportunities to combine present- and future-oriented approaches when studying locations and scales for closing material loops. An example can be found in a study I co-authored for the Province of South Holland, which prioritized scarce industrial land for CE activities. Future oriented approaches, including scenario development, policy reviews, and export workshops, were used to identify criteria for selecting industrial sites for CE. Present oriented approaches, including spatial analysis of data on current shipping and company locations, were used to identify existing hotspots of CE activity. By combining insights from both approaches, the study provided a nuanced recommendation for which industrial sites to prioritize in the province. For the publication, see the “list of publications” section (Van den Berghe et al., forthcoming).

8.2.5 Tension 5: Quantitative and qualitative

The methods used for determining the locations and scales of closing material loops can be categorized into two types – quantitative and qualitative. For this research, quantitative methods were used to statistically analyze large spatial datasets. Datasets included location data on waste, companies, industrial land, material stocks; and analysis methods included mapping, spatial autocorrelation, regression, site selection, spatial optimization. This research also used qualitative methods to analyze textual data consisting of written or spoken words, including policy documents, academic literature, and interview transcripts. Methods included document review and interviews. In this dissertation, the two methods are supported by two opposing philosophical stances – constructivist versus positivist (Maxwell and Loomis, 2010; Creswell, 1994; Guba and Lincoln, 1989).

Quantitative methods are positivist, believing that there is an objective reality that exists independently of human perception, and that this reality can be understood through the objective observation, measurement, and experimentation of quantitative data. Positivist methods are replicable, generalizable, and rigorous. This can be seen in chapters 5 and 7, where statistical and mathematical methods were used to analyze large spatial datasets. This created results that are replicable and generalizable, if suitable data is available. Academic rigor was ensured by well-established and tested methods.

However, positivist methods tend to simplify complex phenomena by reducing them to measurable variables, overlooking subjective aspects, potentially leading to a biased understanding of phenomena. This can be seen in chapters 5 and 7. Chapter 5 reduces factors that influence the locations of CE activity into a small number of quantitative indicators. Chapter 7 reduces location factors of circular hubs into constraints in the optimization algorithm. This results in a simplified optimal solution of setting up 29 hubs in the Metropolitan Region of Amsterdam, which does not consider the political and social aspects of setting up these facilities.

Qualitative methods are constructivist, emphasizing that knowledge is not discovered but rather actively constructed by individuals based on their subjective experiences, and that different interpretations of reality can coexist. Constructivist methods emphasize the role of social and cultural contexts, providing a comprehensive understanding of how these contexts shape knowledge and reality. This can be seen in chapter 3 which examined social and cultural contexts to identify drivers and barriers for circular urban manufacturing; and chapter 6, which examined the political and business contexts which influenced the spatial parameters for establishing circular construction hubs.

However, constructivist methods heavily rely on interpretation, which can introduce subjectivity and potential biases. Moreover, findings may be highly context-dependent and may not be easily generalizable. In this research, the concepts of CE, circular urban manufacturing, and circular construction hubs were derived from literature reviews and interviews conducted using sources from highly developed, wealthy, and western countries, especially North-western Europe. While stakeholders in these regions are motivated to implement these solutions, they may not be applicable to other countries, which have different political priorities, cultures, and economic statuses.

It is evident that qualitative and quantitative methods are suitable for different aspects of spatial research for CE. Qualitative methods are suitable for identifying goals and parameters for the future. For spatial research in CE, this includes (but is not limited by):

- Exploring alternative paradigms other than CE, such as degrowth (Hickel et al., 2022) or doughnut economy (Raworth, 2017).
- Prioritizing focus areas for the CE transition, in terms of industry (e.g. construction, agriculture, manufacturing), materials (e.g. concrete, timber, plastic), or processes (e.g. recycling, remanufacturing, repair).
- Contextualizing CE related land requirements with other priorities for land usage, such as housing, biodiversity, health, and energy.
- Determining spatial parameters for CE facilities, such as circular construction hubs. This can be done by translating business models requirements into spatial requirements.

Quantitative methods translate qualitative goals and parameters into objective measurements and results. For spatial CE research, this includes descriptive, diagnostic, and prescriptive methods (Kristoffersen, 2020).

- Descriptive methods can involve mapping of hot spots for CE activity, such as circular companies, waste producers, processors, and re-users; as well as material stock and flow mapping.
- Diagnostic methods explain why phenomena are located where they are. For CE research, this includes identifying factors that affect the locations of materials or companies using spatial correlation or regression.
- Predictive methods simulate future (environmental, economic) impact of CE scenarios using quantitative methods such as agent based modeling or spatial optimization.

Qualitative and quantitative methods can be combined in different ways in spatial CE research. Firstly, qualitative methods can be used to define the goals and parameters of quantitative methods. This can be seen in chapters 6 and 7, where the spatial parameters identified from interviews with circular hub managers in chapter 6 were applied as constraints to the spatial optimization algorithm in chapter 7. Secondly, quantitative methods can be used to verify theory or hypotheses resulting from qualitative methods. This can be seen in chapters 3 and 4, where chapter 4 used spatial correlation to verify the drivers and barriers for circular urban manufacturing identified in chapter 3. Finally, qualitative methods can be used to interpret results from quantitative methods. This approach could be applied to chapter 7 in future research, where the optimal scales and locations of circular hubs can be discussed with key stakeholders in the area to verify and explain the (in)validity of the results.

TOC

8.3 Limitations and future research

This dissertation has two main types of limitations - conceptual and methodological. The following paragraphs explain each limitation and corresponding recommendations for future research.

8.3.1 Conceptual limitations

When defining closing material loops, this thesis focused on end-of-life strategies (waste-to-resource processes) rather than other strategies, such as life extension and industrial symbiosis. This is reflected in the spatial datasets used - locations of waste reuse in chapter 5, and future supply and demand of construction waste in chapter 7. This creates an incomplete picture of the circular economy, especially for the construction sector, since material demands for renovation and maintenance of buildings can be equal or even greater than for construction of new buildings. Future research can analyze datasets for other circular processes, using the spatial analysis methods introduced in this thesis. For example, spatial parameters can be gathered for facilities that enable product life extension, such as repair cafes and thrift stores. Spatial optimization could consider material requirements for renovation and maintaining buildings when matching future supply and demand for secondary materials.

When measuring the environmental impact of material stocks and flows, this thesis focused on weight rather than carbon emissions as a unit of measurement. This reflects a larger research gap in CE research, where material stocks and flows are generally measured in tons or kilograms. This leads to a biased emphasis on industries associated with a high tonnage of materials, and not necessarily a high environmental impact. The construction industry is a prime example: the waste reuse dataset used in chapter 5 was dominated (in weight) by concrete aggregate, while recycling this material does not necessarily lead to the highest emissions savings. Future research can use carbon emissions as a unit of measurement rather than weight. This can be applied to spatial clustering and correlation studies by converting kilograms of materials to tons of CO_2 in embodied carbon emissions. Future spatial optimization studies can also study environmental impact in more detail by considering carbon emissions associated with an entire waste-to-resource supply chain - collecting, storing, processing waste, then producing a new product. This could be done by conducting spatial optimization for a specific product, if a life cycle analysis was already conducted.

8.3.2 Methodological limitations

The research scope of this dissertation is limited to the Netherlands, and in later chapters, Amsterdam. The area's unique characteristics, including high political priority for circular economy and abundance of spatial data, makes the findings of this research difficult to generalize to other regions. Future research can attempt to apply the same spatial analysis methods used in this dissertation to other geographical areas. Because there is limited data available on material stocks and flows, studies on site selection for circular facilities based on spatial parameters is likely the lowest hanging fruit, since data for this type of study is readily available (OpenStreetMap contributors, 2017). An example can be seen in the selection of circular maker space locations for EU Horizon research project Pop-Machina (Çay et al., 2023).

This dissertation focused on spatial analysis methods. However, there are a number of non-spatial data analysis methods that could be equally valuable to CE research – the analysis of networks and time. Network analysis can increase understanding of the entire waste-to-resource supply chain as a network, rather than looking at each step (waste production, processing, reuse, hubs) as individual locations. Rather than looking at locations, clustering, and scale; network-related characteristics, such as centrality and between-ness, and can be analyzed for circular supply chains. Temporal analysis can increase understanding on how CE locations change over time. This analysis is already possible, as some material datasets already have a time component (LMA dataset, urban mining datasets). Having an understanding of time will allow researchers to better identify trends, and predict potential future scenarios.

The results and recommendations from this dissertation were not tested with spatial planners to determine their validity and utility. Future research can include interviews and workshops with key spatial planning stakeholders in the region, where solutions proposed by this research, such as the optimal number and locations of circular timber hubs in Amsterdam, can be further enhanced by the social, political, and economic concerns of the region.

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TOC

Curriculum Vitae

Tanya Tsui (1994) was born in Hong Kong, where she studied for a Bachelor's degree in Architecture at the University of Hong Kong. After graduation, she worked as an architecture assistant at three not-for-profit architecture firms: Rural Urban Framework (rufwork.org), designing and managing building projects in rural China; DOMAT Architecture (domat.hk), designing flexible furniture for subdivided housing residents in Hong Kong; and Azia Chaouni Projects (azizachaouniprojects.com), designing a music school in M'hamid El Ghizlane, Morocco. She then studied for a Master's degree in Architecture at the Delft University of Technology, where she learnt about sustainability and circular economy and discovered an interest in research.

After her studies, she continued to work at the Delft University of Technology as a research assistant under the supervision of Dr. David Peck, working on European funded research projects on circular economy, critical materials, and remanufacturing. In 2019, she started her PhD research on circular economy, thanks to research funding provided by the European Horizon 2020 research project Pop-Machina (pop-machina.eu), under the supervision of Prof. Arjan van Timmeren, Dr. David Peck, and Dr. Alexander Wandl. Throughout her time as a researcher at the Delft University of Technology, she also led a seminar teaching research design skills to architecture masters students in the Architectural Engineering and Technology course together with Mo Smit and Annebregje Snijders.

One year into her PhD and in the midst of the COVID-19 global pandemic, Tanya taught herself how to code in Python, which dramatically changed the course of her PhD research: moving from understanding the role of maker communities in a circular economy, to conducting quantitative geospatial analysis on material stock and flow datasets. She collaborated with a number of co-authors with her new found interests: Dr. Alexis Derumigny on spatial clustering, Arjang Tajbakhsh on facility allocation for food waste facilities, Karel Van Den Berghe on industrial site selection for the Province of South Holland, and Titus Venverloo, Fabio Duarte, and Tom Benson on spatial optimization of circular hub at the MIT Senseable Amsterdam Lab.

TOC

List of publications

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Tsui, T., Peck, D., Geldermans, B., & van Timmeren, A. (2020). The Role of Urban Manufacturing for a Circular Economy in Cities. *Sustainability*, *13*(1), 23. https://doi.org/10.3390/su13010023

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Forthcoming publications

Tsui, T., Duarte, F., Venverloo, T., & Benson, T. (Forthcoming). Spatial optimization of circular timber hubs [Preprint]. In Review. https://doi.org/10.21203/rs.3.rs-3013682/v1

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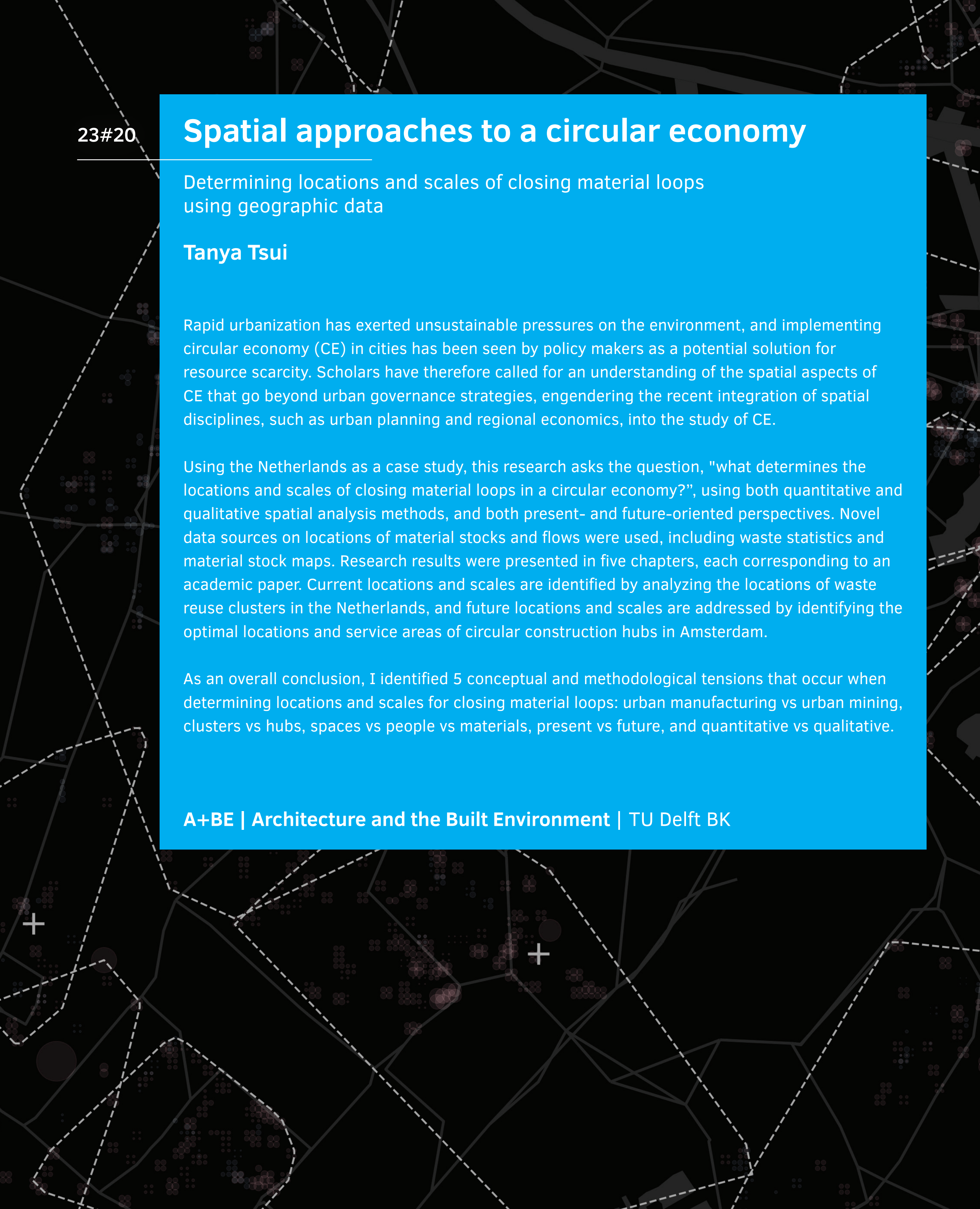
Van den Berghe, K., **Tsui, T.,** Nefs, M., Iliopoulos, G., Papadimitriou, C., Fitzgerald, T., Bonte, T., Arrindell, A. (Forthcoming) Planning the circular economy: using fore- and back-casting methodologies to deal with uncertainty. *Cambridge Journal of Regions, Economy, and Society.*



23#20

Spatial approaches to a circular economy

Determining locations and scales of closing material loops using geographic data

Tanya Tsui

Rapid urbanization has exerted unsustainable pressures on the environment, and implementing circular economy (CE) in cities has been seen by policy makers as a potential solution for resource scarcity. Scholars have therefore called for an understanding of the spatial aspects of CE that go beyond urban governance strategies, engendering the recent integration of spatial disciplines, such as urban planning and regional economics, into the study of CE.

Using the Netherlands as a case study, this research asks the question, "what determines the locations and scales of closing material loops in a circular economy?", using both quantitative and qualitative spatial analysis methods, and both present- and future-oriented perspectives. Novel data sources on locations of material stocks and flows were used, including waste statistics and material stock maps. Research results were presented in five chapters, each corresponding to an academic paper. Current locations and scales are identified by analyzing the locations of waste reuse clusters in the Netherlands, and future locations and scales are addressed by identifying the optimal locations and service areas of circular construction hubs in Amsterdam.

As an overall conclusion, I identified 5 conceptual and methodological tensions that occur when determining locations and scales for closing material loops: urban manufacturing vs urban mining, clusters vs hubs, spaces vs people vs materials, present vs future, and quantitative vs qualitative.

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