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Chapter 2
Geographic Information Systems for Circular Cities and Regions

Tanya Tsui, Wendy Wuyts, and Karel Van den Berghe

Abstract A geographic information system (GIS) stores, manipulates, analyses, and visualises spatial data. GIS enables the mapping of building elements and components and can optimise the location of facilities for circular activities, thus contributing to the closing of material loops and the spatial development of circular cities and regions. This chapter presents use cases of GIS in the circular built environment, with examples from academia, industry, and government. Academics use GIS data for urban mining studies to estimate the location and availability of secondary construction materials. Businesses in industry use GIS analysis to inform the facility location of circular construction hubs and (reverse) logistics. Governments use GIS to monitor and assess the circular spatial development potential of their (industrial) territories. In order to integrate GIS into circular economy solutions, improvements need to be made in making spatial data available and in presenting findings that emerge from it. Finally, present enthusiasm for GIS tools should be balanced by a deeper understanding of the connection between digital tools and governance decisions.

Keywords Geographic information systems · GIS governance tools · Spatial data · Spatial analysis · Circular cities

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T. Tsui (✉) · K. Van den Berghe
Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands
e-mail: t.p.y.tsui@tudelft.nl

W. Wuyts
Department of Civil Engineering and Manufacturing, Norwegian University of Science and Technology, Gjøvik, Norway

Omtre AS, Hønefoss, Norway

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2.1 What Is GIS?

A geographic information system (GIS) is a system for managing, analysing, and visualising geographic data. Geographic data integrates location data (where things are) with all types of descriptive information (what things are like there). GIS is utilised in multiple technologies, processes, techniques, and methods, and it is associated with various disciplines, including engineering, planning, management, logistics, telecommunications, and business. The ubiquity of GIS can be attributed to the fact that a large variety of problems are affected by their location and thus can incorporate the use of location data (Goodchild 2010; Chang 2018).

2.2 GIS in the Built Environment

Within the built environment, GIS is used as a tool to create, share, and analyse spatial data. Spatial data related to the built environment can be created from processing data sources such as satellite images. This can be seen in the creation of high-resolution 3D models of cities using photogrammetry (ArcGIS 2023a), LiDAR (laser imaging, detection, and ranging) (TU Delft 2023), and Google Street View data (Spotr 2023; Chap. 3 by Gordon et al. on scanning technologies). These models are especially relevant for the built environment: 3D data is essential for various analyses, including estimations of wind load, solar exposure, and temperature changes in city blocks or neighbourhoods.

Spatial data can also be visualised and shared, allowing stakeholders to track and maintain elements in buildings, infrastructure, and even cities. Tracking is often achieved in combination with other digital technologies, such as building information modelling (BIM). This can be seen in the tracking and tracing of urban infrastructure (ESRI 2020), as well as city management systems that crowdsource citizens' maintenance requests for their municipality on a map (Liu 2021). The tracking of elements in the built environment can be seen in the development of digital twins – virtual models of the built environment that store detailed information on urban elements, such as buildings, greenery, and infrastructure.

Finally, spatial data can be analysed to create insights and aid decision-making in the built environment. This can be seen in transportation optimisation (Santi et al. 2014), site selection of services (Kontos et al. 2005), analysing energy potential (van den Dobbelsteen et al. 2011), and urban morphology (Spatial Morphology Group 2023).

2.3 GIS for a Circular Built Environment

In recent years, researchers from industrial ecology, economic geography, and urban planning have highlighted the importance of space as a major factor in the study of circular economy (Wuyts et al. 2022; Bahers et al. 2022; Bucci et al. 2022). Creating, sharing, and analysing spatial data in GIS can therefore bring further insights and aid decision-making in a circular built environment. This section provides a brief overview of GIS for a circular built environment through creating, mapping, sharing, and analysing spatial data. Section 2.4 provides detailed examples of these methods, introducing cases from academia, industry, and government.

GIS's capability in creating and mapping spatial data can be used to visualise material flows and the availability of secondary material and land. Existing spatial data can be used to map out the availability of secondary materials embedded in buildings today in a process known as 'urban mining' (Van den Berghe and Verhagen 2021). An example can be seen in Fig. 2.1. Flows of secondary materials can be mapped using transportation data or waste management data. The mapping of stocks and flows can highlight hotspots with a high concentration of available secondary resources or the presence of material reuse. This information can then be used to assist the planning of the location of material reuse actors – facilities that collect, store, and redistribute construction waste to be reused in new construction sites, thus narrowing and closing material loops (see Sect. 2.4.1).

Sharing spatial data in GIS platforms allows for tracking buildings, infrastructure, and waste flows. Tracking the conditions of buildings and infrastructure allows

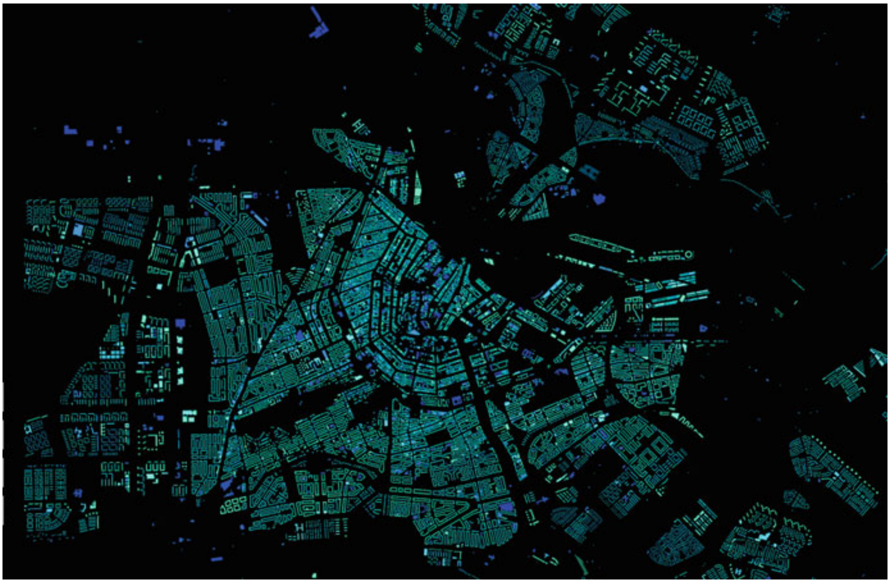

Fig. 2.1 Mapping of copper availability in Amsterdam, using open data on residential buildings (Waag 2016)

maintenance and repair works to be conducted in a coordinated and timely manner, which ensures a longer life cycle, resulting in the slowing of material loops. Digital platforms, which allow for the exchange of secondary materials, often have a mapping element that allows users to know the locations of stakeholders (Rotor 2023; Superuse 2023) (see also Sects. 2.4.2.2 and 2.4.2.3). By tracking waste material flows, governments can also monitor their level of circularity and transportation emissions, giving policymakers a better understanding of their progress towards circularity (see Sect. 2.4.3).

Finally, spatial data analysis in GIS can create insights that aid decision-making in a circular built environment, often at a city or regional scale, for closing material loops. By analysing spatial parameters of locations such as accessibility and proximity to amenities, site selection and facility location analysis can be conducted to find suitable locations for circular activities, such as facilities for recycling or remanufacturing (see Sects. 2.4.2.1 and 2.4.3.1). Clustering analysis can be conducted on hotspots of circular industrial clusters, highlighting areas that could further scale up their circular activities in closing material loops (see Sect. 2.4.1). Network analysis can be conducted on (circular) supply chains, allowing policymakers to identify important players in a network of secondary material flows. Stakeholders in (circular) supply chains can be identified using a dataset that represents locations of material flows, such as waste statistics or shipping movement data (see Sect. 2.4.3.1).

2.4 Example Use Cases

The following subsections present use cases of GIS in the circular built environment, with examples from academia, industry, and governments.

2.4.1 Academia

Academia has played a role in the development of GIS in circular built environment research and in improving the accuracy of estimating future locations of secondary material availability in cities, identifying optimal locations for circular infrastructure, and developing circular city information infrastructures.

2.4.1.1 Estimating Locations of Future Secondary Material Availability: From a Top-Down to a Bottom-Up Approach

One of the most well-known mapping and accounting methods in circular economy research is material flow and stock analysis (MFSA). This method is rooted in the scholarship on societal metabolism and has a history of theoretical developments and methodological advancements since the nineteenth century (Fischer-Kowalski 1998). MFSA was mostly done with statistical data and in a top-down approach based on the accounting principle of mass balance, where a stock of materials is seen as the difference between inflows and outflows of a certain material in a certain area (often an administrative unit) for a time period (usually a year) (Lanau et al. 2019). Often, top-down approaches use statistical data of the amounts of the materials without specific building location instances, which makes it difficult for interested parties to locate where and when these materials could become available for future reuse.

In 2009, Tanikawa and Hashimoto published a seminal paper which proposed using GIS data for estimating material flows and stocks (Tanikawa and Hashimoto 2009). Integrating GIS provides information about the location and timing of the availability of reclaimable materials. By incorporating spatial data using GIS, the results of MFSA become useful for specialised deconstruction companies, urban miners, and other reuse actors at the local level, in contrast to nonspatial MFSA (Wuyts et al. 2022). If there is a time series of GIS layers (cadastral data), researchers can study patterns, such as the average life span of buildings, categorised according to building year or period. This can be used as input in estimating the future potential supply of (secondary) materials from demolition (Van den Berghe and Verhagen 2021).

While many practitioners and academics still use the top-down approach and the EUROSTAT compilation guidelines (European Commission 2018), Tanikawa and Hashimoto’s work has inspired more researchers to use a bottom-up approach, shifting towards more local estimations of material stocks and flows (Wuyts et al. 2022). This approach entails the quantification of materials in a certain location (e.g. a building) by multiplying the area of the location (e.g. in square metres) by the material intensity coefficient typical for the building or location (e.g. tonnes of a certain material per square metre). The coefficient refers to the material intensity, which is derived as part of a multiplication with the volume of that material present in that building. The coefficients are often based on existing planning documentation retrieved from archival work, communications with the demolition or construction companies, on-site investigations through laser scanning (see Chap. 3 by Gordon et al. on scanning technologies), or, if available, BIM models (Sprecher et al. 2022; Honic et al. 2023). However, these material intensity coefficients are different for the period, the location, and the functional unit, as, for example, demonstrated through comparing material intensity databases in the Canadian city of Toronto, the Australian city of Perth, and the island of Luzon in the Philippines (Arceo et al. 2023). These databases of material intensity coefficients are often not organised in standard structures, which makes comparisons and data exchanges difficult.

In addition, this bottom-up approach, often called the ‘coefficient-based approach’, requires a lot of data and is labour-intensive but provides spatial information on the specific building location. These coefficients are multiplicated by gross volumes, often derived from cadastral data, and the outputs are maps showing where materials are located in a geographical area. When materials embedded in buildings are seen as future urban resources, mapping them is like developing an inventory of future available materials. Hence, associated researchers have been developing urban resource cadastres for a circular economy in European cities, such as in Odense, Denmark (Lanau and Liu 2020), Vienna, Austria (Kleeman et al. 2017), and Gothenburg, Sweden (via CREATE project, 2022–2025). In some cases, researchers can predict when these materials could become available for future reuse, via municipal demolition and construction agendas (cf. building permits), or if time-related data (such as building ages and average life spans of buildings) is available. While most cadastral data is digitally available, older cadastral data can be digitised using artificial intelligence and machine learning methods (e.g. see the Nested Phoenix in Melbourne and Brussels (Stephan et al. 2022)).

The outputs of coefficient-based approaches in MFSA can inform urban mining studies and plans, thus helping to estimate and visualise the location, availability, and reusability potential of secondary construction materials within cities and regions (Wuyts et al. 2022). An academic cluster of researchers associated with Tanikawa and Hashimoto is using their method to collect data for informed decisions for sustainable urban and regional development. For example, Guo et al. (2021) used this method for estimating the material stocks and flows as well as the lifetime of buildings over a chronicle in Tiexi district of the Chinese city Shenyang. This district is often seen as a microcosm of Chinese studies and representative of many Chinese urban neighbourhoods.

Building upon coefficient-based approaches in MFSA, researchers have started investigating how this method can help the circular economy transition in the built environment. One of the explorations is the combination of insights from historical studies, political economy, and innovation with spatially explicit material stock studies. GIS is used twice: first to map the material stocks, and then to make an estimation model of where vacant sites are (and, thus, where materials could be available for reuse) (Wuyts et al. 2020). However, this approach should not be used without critical thinking. First of all, predictive or speculative mapping of vacant sites for future mining can be seen as a colonial capitalist practice that erases the histories and presences of specific groups of people and other beings (Noterman 2022). Second, it is important to note that mining the materials and reusing construction materials is a short-term perspective, while a long-term perspective is renovating and repurposing these constructions, and a multispecies perspective is giving the land back to other species and letting it overgrow (Wuyts and Marjanović 2022; Marin and De Meulder 2021a).

All these methods often require specialised equipment and consume time and large file types and databases, especially if some data is retrieved through laser scanning (Uotila et al. 2021). A promising new approach for locating reclaimable materials is using data from street-view images (e.g. Google Street View) of facades to train machines to create classification maps that can assist in defining protocols and urban planning, as demonstrated in Zurich and Barcelona (Raghu et al. 2022). (See Chap. 4 by Armeni et al. to learn more about artificial intelligence and image recognition for reuse.)

2.4.1.2 Identifying Locations of Existing and Future Circular Facilities Using Spatial Analysis

GIS can be used in speculative mapping studies to understand the location of existing and future facilities and infrastructure associated with a circular built environment. Speculative mapping or cartography is a tool to make the future or frontier visible for extracting potential resources (Noterman 2022). In the circularity context, this frontier could be possible locations of reclaimable secondary materials or circular infrastructure (Tsui et al. 2023). Speculative mapping is often used in urban planning. In Belgian cities such as Brussels and Leuven, landscape architects are using GIS to map circular practices within an area or landscape. By doing so, they map and speculate how a facility such as a 'material bank' can facilitate circularity in a city (Marin and De Meulder 2021b). Verga and Khan (2022) created an urban circular practice atlas in Brussels, which is a combination of different GIS layers for different facilities and organisations for different sectors that shows the spatial configuration of logistic infrastructure such as collection points for different material flows (e.g. textile, construction materials).

Furthermore, GIS can be utilised to conduct spatial statistical analysis to identify optimal locations of present and future circular facilities – whether they are facilities for waste recycling or hubs for material exchange. In the Netherlands, spatial analysis is conducted to quantify the spatial clustering of waste reuse activities, as well as to find hotspot locations for waste reuse (Tsui et al. 2022). Further work was also conducted to estimate the optimal number and locations of concrete recycling plants in the Netherlands (Hodde 2021). In industrial symbiosis, proximity is key, which requires local optimisation calculations requiring GIS (e.g. see Yu et al. 2021).

Other researchers build further on spatially explicit material stock studies stored in GIS, where origin-destination calculations are conducted to criticise missing infrastructures for recycling concrete in a city, such as Den Hague (Van den Berghe and Verhagen 2021). In Singapore, spatially explicit material stock studies were performed to estimate the potential of building materials that could be transferred to the growing housing market in Indonesia, which is only a few kilometres away (Arora et al. 2019, 2020). Spatially explicit material stock and flow studies have been shown to benefit circular city implementation (Wuyts et al. 2022).

2.4.1.3 Developing Circular City Information Infrastructures

Different cities are developing circular city information infrastructure to monitor and support policy planning. Mostly the information is analytical: digital twins are developed, (top-down) indicators are refined, and material flows are mapped. In Flanders, Belgium, the Vlaamse Open City Architectuur (VLOCA 2023) hosts a knowledge hub for smart cities. Other similar initiatives include the circular economy monitor in Flanders (Vlaanderen Circulair 2021), Ganbatte World (Ganbatte

World 2023), and the Amsterdam circular economy monitor (Gemeente Amsterdam 2023). However, none of these initiatives integrates experiential knowledge, avoiding the fact that cities are also experiential information systems (De Franco and Moroni 2023).

In 2022, NTNU Sustainability at the Norwegian University of Science and Technology funded the Circular City Project (2022–2026). The researchers will apply a bottom-up technique to assist Trondheim, Norway, in catalysing circular material flows (NTNU 2022). The idea is to create digital twins of individual buildings within the larger city-scale digital twin of Trondheim, fusing macro-level data (GIS layers, with graph data) with micro-level data such as BIM objects. This application is similar to a research project on modelling and predicting building blocks in Vienna, where BIM models provided a material intensity database that could be multiplied by the gross volumes obtained from GIS (Honic et al. 2023).

A wide array of GIS applications in academia are working towards the circularity transition of the built environment industries. These GIS techniques are beginning to leave the academic sphere, leading to action in industry and government, as seen in the section below.

2.4.2 Industry

The following section provides an overview on how GIS is used in industry for a more circular built environment. Industry uses GIS to plan locations of reuse infrastructures, to track locations of components and materials via digital platforms, and to facilitate the efficiency of reverse logistics.

2.4.2.1 Planning Reuse Infrastructures

Companies such as reclaimable material brokers and manufacturing companies use GIS analysis to inform their spatial strategies for facility location of circular construction hubs and (reverse) logistics. In southern Norway, more than 30 partners, representing different actors of the forestry, timber construction, deconstruction, waste industry value network, and research institutes, started the SirkTRE consortium and received funding for research, development, and innovation projects in 2021–2024 (SirkTRE 2022). The first phase encompassed a stakeholder mapping process, including missing roles. One of the missing roles was circular hubs where wood waste, mostly from demolition projects, would get collected for quality check and pretreatment (drying, removing hazardous substances, cutting it ready for industrial sale) and assembly in new building elements and components. In Belgium and Norway, these circular hubs were more the result of the availability of land, often placed in restored brownfields (e.g. Materialenbank Leuven in Belgium; Omtre’s Materialenbank in Hønefoss, Norway) or vacant public spaces that are in development (e.g. Sirkulær Ressurssentral in Oslo, Norway).

Because stakeholders wanted to deal with high material volumes and withstand higher investment risks, the planning went through a methodology cocreated by SirkTre consortium partners, external consultants, and seed funders. In early 2022, Omtre AS started the planning of a circular hub to be in operation before 2030 and collected insights from Norwegian experts but also looked at the existing and emerging circular hubs in Belgium and the Netherlands. Informed by theories from economic geography, investigations will be made in different locations, spatial configurations, and setups (e.g. temporary vs permanent) under different input parameters and future scenarios. One of the research-for-informed-planning tasks considers a forecasting GIS-material stock analysis to estimate the potential availability (when, where, and how much) of various wood waste fractions of demolition projects. Noteworthy is that this spatially explicit material and flow analysis will not follow standard MFSA guidelines by going beyond administration boundaries. Omtre uses the metaphor of the circumference. At a UNESCO site at the former mining mountain town of Røros, Norway, mining happened within a circumference because of the location of the copper and the economic costs related to the transport of the copper and the input resources (e.g. trees for fire). Since it is seen as reasonable to drive 2 hours to pick up materials in the Norwegian cultural context, this distance is the radius of the circumference for urban mining.

Omtre AS is also setting up GIS to map existing infrastructure (e.g. storage, transport, etc.), power relationships, technical lock-ins (risks), and required partnerships to enable the relocation of building materials. This data collection task has two objectives. First, it will inform a speculative mapping of how a material bank facilitates timber flows (inspired by Marin and De Meulder 2021b). Second, it will feed the setup of an optimal routing calculation of the collection of the selected wood waste fractions and distribution of the building materials and elements to construction sites or intermediary partners (e.g. prefabricated module builders).

2.4.2.2 Tracking and Tracing via Digital Platforms

Presently, digital platforms are emerging to enable circularity practices such as reusing building materials and components, selling tools or advice, calculating life cycle costs, or even providing a marketplace (Wuyts et al. 2023). In this chapter, we are interested in the functionality of tracking and tracing the locations of buildings, elements, or materials using GIS. In some circularity practices and strategies, geographical proximity matters. Industrial symbiosis platforms are taking the role of intermediary third parties that match supply and demand (Krom et al. 2022) – often by sharing not only data on available materials but also other resources (storage space, equipment, trucks). These platforms require GPS coordinates, so the logistics of the relocation can be arranged and optimised. Especially in industrial symbiosis, proximity is key and requires the integration of GIS (e.g. Yu et al. 2021).

Digital platforms can provide two services: tracking and tracing. Tracking is recording data on where the material is at the moment. Tracing means knowing where the material comes from, including its history and exposure to harmful events.

Tracing can help estimate risk and identify which application the material could be used for. Tracing is also key in the increased demand for transparency and social sustainability controls, especially upstream of the value chain. Tracking and tracing are presently already part of cyber logistic systems. Here, GIS is used to automatically calculate the optimal routing when moving materials or components from one location to another.

There have been speculations that material banks and other temporary storage spaces will become obsolete in the future and will be replaced by systems that track the required materials in planned demolitions and constructions and facilitate a direct relocation of materials from the deconstruction to the construction site. These digital solutions would substitute spatial requirements (e.g. land and infrastructures needed for storage). Nevertheless, due to the conservatism of the construction sector and the slow uptake of digital solutions in general, the rapid wide deployment of digital solutions replacing spatial requirements is not expected.

2.4.2.3 Tracking in Reverse Logistics and Remanufacturing

While digital markets match different building industry actors and can facilitate the optimisation of logistics of the reclaimed building material from one actor to another (Sect. 2.4.2.2), the relocation of materials can also happen via reverse logistic systems within the same company's value chain. Optimisation of logistics from a building to a remanufacturing plant and again integration in the old or new building project is again key to reducing the costs of remanufacturing. As part of the linear economy, these companies have normally established internal tracing and tracking systems which enables the logistic managers to follow a product (often only within the factory boundaries) until the ownership of the product is transferred to the next actor in the value chain.

One important step for enabling tracing and tracking is that products get tagged with a label or a unique identifier (e.g. barcode or QR code). Later, in the value chain or during the use or demolition phases, this label can disappear for various reasons, and the connection with a digital tracking and tracing system can get lost. Hence, setting up reverse logistic systems often means the creation of a new tag at the source of the collection of secondary materials (e.g. waste collection points, which would become the new point zero of the tracking system). If companies create tags which will not disappear, they can set up a signalling system when these materials should be reclaimed and transferred back for remanufacturing into the current or new building projects. (For more information about information needs for the complex process from deconstruction via reverse logistics to remanufacturing, see Chap. 11 by van den Berg.)

Different companies in the circular built environment transition look into different labelling systems that contribute to tracking and tracing, even over different life cycle phases of the material and when it is owned by other actors. Are barcodes or QR codes the right tags from a reuse perspective, knowing they can disappear in the use or deconstruction phase? For example, in the timber construction industry, the constellation of the knots in each wood element – or so-called wood fingerprint – is unique and can be recognised with cameras of scanners (e.g. Pahlberg 2017); it could be used as a natural QR code which can be scanned at any life cycle phase, from forest to second or third use cycles. These tags or unique identifiers are coupled with data from industry foundation classes (IFC), which is a data exchange schema describing architectural, building, and construction industry data. There are developments where the geolocation of products would be part of IFC specifications. If these geolocation requirements were part of IFC data in tracking, this would create information about where products end up in the first use cycle and also in the second, third, and next-use cycles, which would lead to insights about environmental impacts related to transport and on the service time of these products in that location and building. (See Chap. 5 by Honic et al. for the role of data templates and material passports in tracking assets over more life cycle phases.)

2.4.3 Government

Governments use GIS to monitor circularity in their areas of jurisdiction and to assess the circular spatial development potential of (industrial) land. This section will introduce two examples: Project Zuid-Holland and the RePair project.

2.4.3.1 Project Zuid-Holland: Prioritising Industrial Land for the Circular Economy

Project Zuid-Holland (South Holland) is a collaboration between the Delft University of Technology and the Province of Zuid-Holland in the Netherlands. The aim of the project is to evaluate the importance of water-bound industrial areas in the province in accordance with its existing and future needs, with a special emphasis on the transition to a circular economy. The project arose from the province's need to prioritise the preservation of its existing scarce industrial areas. In many municipalities within the province, existing water-bound industrial areas are being transformed into residential and commercial land use that do not take advantage of the spatial and logistical possibilities of industrial activity and water transport for circular activities such as locally reusing or recycling construction materials. Responding to a lack of understanding of circular economy from a spatial perspective, this project focuses on the spatial requirements for future transitions. This includes location conditions such as available firms and technologies, the presence and diversity of labour forces, environmental restraints, and logistical multimodal possibilities. This leads to the question: What spatial planning strategies are necessary for the current and future stock of water-bound industrial areas in Zuid-Holland in order to foster future transitions?

The project has three main work packages: (1) mapping existing water-bound industrial areas, (2) determining spatial requirements for future transition-related activities, and (3) offering policy recommendations. The first work package, mapping of water-bound industrial areas, uses GIS to generate insights for the subsequent deliverables. The mapping process includes two main steps: the topographical mapping of existing commercial and industrial activities and the topological movement of materials via water transportation infrastructure. By using spatial data on the locations of commercial companies, a map was created showing industrial land within the region that hosted circular economy-related industries. Additionally, shipping data was used to identify industrial lands that were visited by ships, indicating the utilisation of water transportation. The spatial analysis work of the project resulted in two maps. The first is a geographical map of industrial sites in the province, showing whether each site was water bound, if it utilises water transport, and if it contains circular industries. The second is a network map (or diagram) showing which industrial sites are connected to each other via water transportation, as well as highlighting industrial sites that are strongly connected within the network.

To summarise, this project addresses circularity by deepening our understanding of the circular economy transition from a spatial perspective (for the full report, see Van den Berghe et al. 2023). Spatial analysis allows key industrial sites to be selected and prioritised for future circular activities, contributing to narrowing, slowing, and closing material cycles.

2.4.3.2 The RePair Project: Geo-design Decision Support Environment for Circular Spatial Strategies

Funded by the European Commission, the RePair project (2016–2020) (RePair 2023) aimed to develop a methodology that allowed for the creation of integrated, place-based, and eco-innovative spatial development strategies to reduce waste flows in periurban areas. The methodology was implemented in six metropolitan areas, using a geo-design decision support environment (GDSE) in multiple workshop settings. This method extends the assessment of urban metabolism to include concepts related to urban drivers, urban patterns, environmental and spatial quality, and potential co-benefits of strategies.

GDSE is a digital platform based on the geo-design framework, which allows for a geographical study area to be described, evaluated, and (re-)designed according to a predetermined goal (Steinitz 2012; Arciniegas et al. 2019). The GDSE combined and visualised spatial data collected from local contexts, such as locations of waste production and processing, land use, and company location data. An example of this can be seen in Fig. 2.2, showing the movement of waste to and from Amsterdam. This information was presented within a series of workshops to key local stakeholders in the development of a circular economy, including planning authorities, public/private organisations involved in strategic environmental assessment, and industrial actors in waste and resource management. The workshops with key stakeholders were used to aid decision-making in the development of place-based spatial development strategies for each of the six metropolitan areas.

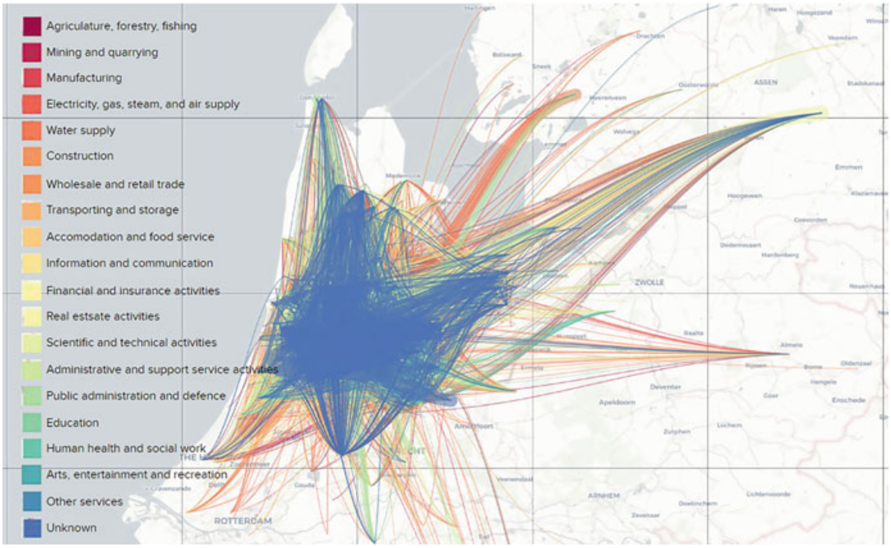

Fig. 2.2 Mapping waste flows in Amsterdam (Furlan et al. 2020)

The project resulted in the creation of a spin-off company, GeoFluxus (GeoFluxus 2023), which provides material flow monitoring services to governmental bodies and private companies. Using material and waste statistics, GeoFluxus provides insight into where waste streams are available for circular (business) opportunities and develops methods for monitoring those streams at various scales (municipal, provincial, national), thus allowing organisations to measure their progress towards the circular economy.

2.5 Discussion

2.5.1 Connecting to Other Technologies

Collecting spatial data is key in academic research for informing circular city and built environment projects. GIS is at a high technology readiness level (TRL 9), meaning that the technology and information systems are widely known and adopted, in most European and North American regions, and is often integrated with other digital technologies (e.g. BIM) to support circular systemic solutions. Recently, software companies ESRI and AUTOCAD have worked together to smooth data exchange between GIS and BIM graph data (ArcGIS 2023b), allowing higher data transfer speeds and more seamless integration. For better integration of software systems, data handlers need more sensitivity for the different data formats. Some scholars propose standardised structures for databases, such as for organising material intensity data (e.g. Guven et al. 2022) to enable interoperability. Another measure is clear-cut communication between the GIS executioners and information and communications technology (ICT) architects to foster seamless data exchange. For example, one risk is that these systems are designed by ICT architects who do not realise that GIS can be based on graph data and relational database management systems. The shapes used in GIS (polygons, lines, points) can be expressed in graph data, made of arcs and nodes. They are single attributes in a table which can be part of a relational database in the case of software programmes such as ArcGIS and qgis. However, the shapes are not necessarily explicitly related; tabular data can be exchanged instead. Tabular-centric architecture requires more effort to integrate with GIS expressed in graph data.

GIS can also be linked to technologies enabled by artificial intelligence (AI). Machine learning image recognition models can be used to identify reusable building components at an urban scale, using GIS and Google Street View data (Raghu et al. 2022). Additionally, as AI tools become increasingly available to the public, GIS technologies will become increasingly democratised and used by nonexperts. An example of this is ChatGPT, an AI chatbot that not only responds to prompts in text but in computer code as well, allowing users to potentially generate complex code for spatial analysis without prior knowledge (Tsui 2023). While these technologies can greatly empower the general public, it is important to take into account the dangers of releasing tools that are accessible to many but understood by few.

2.5.2 Hurdles and Barriers

In order to integrate GIS with circular economy solutions, a number of challenges need to be overcome. The availability and quality of spatial data, and the way insights are presented, need to be improved. GIS metadata – data about GIS data that provides information such as where the data was collected, who collected it, how it was processed, etc. – is crucial for trustworthiness and transparency, which is especially important to a circular built environment that strongly depends on information facilitation and sharing between different stakeholders (and in times of increased cybersecurity risks). Insufficient metadata often limits understanding of where the spatial data comes from or how it was created. Better metadata leads to more transparency and trustworthiness. There are already various ISO standards for trustworthiness and other frameworks for data and information facilitation (Naden 2019). In terms of data standards, industry actors should ensure that additional GIS data collection does not create more administrative hurdles, such as by necessitating additional agreements on who owns or stores spatial data. One important step forward would be to provide more process standards and data management plans that help define, for example, when to stop collecting and storing spatial data, finding a balance between cybersecurity and circularity.

The development of a circular built environment may also require the involvement of citizen communities. To ensure the participation of citizens, open and public access to GIS-based algorithms and methods would be ideal. Public access to GIS data and methods not only fosters collaboration and involves diverse groups of users (e.g. citizens and communities), but it also allows independent parties to detect possible data biases in algorithms that could discriminate against people of certain backgrounds (Lally 2022; McCall 2003).

2.5.3 Future Trends

The use of GIS for understanding and improving the current state of the circular economy will increase in importance, especially in terms of reducing hurdles in technology compatibility. The most promising future for the technology arguably lies in using GIS as a tool for making governance decisions, such as how to match the demand and supply of materials in time and space. Policymakers often lack the capability to use digital tools, while technology experts who use these tools often are uninformed of policy questions behind their application (Hollands 2020). We warn against the false promise that more quantitative measuring or digital tools will always lead to better results – a correlative but not causal relationship, debated already in the 1980s during the so-called quantitative revolution (Paasi et al. 2018). Additionally, circular city and regional initiatives and their information infrastructures focus mostly on analytical data, not lay or experiential knowledge. Significant progress is needed to bridge this gap.

In the end, GIS remains a tool that is operated by a designer or policymaker, starting with a question. That question must be given focused time and attention. We should thus be cautious about our enthusiasm and investing capacity (be it in financial, R&D, human, or other resources) in developing and applying digital tools such as GIS to solve circular economy problems. Ultimately, understanding why, when, where, and for whom we need a circular economy or circular built environment – and subsequently, why we need better tools – should be prioritised over investing further in the technology without a clear understanding of its utility for circularity. The past should serve as a warning. Although we have been developing tremendously sophisticated digital tools, material passports, and monitoring structures for about half a century, we have and are still losing the fight against climate change, more because of political reasons than a lack of data. If we view the circular economy as a strategy to cope with this climate change, then the same reasoning can be followed: are the digital tools we develop to foster a circular built environment really what we need? The correlation between policy and means needs more attention in research and practice to guarantee a more sustainable circular built environment.

2.6 Key Takeaways

- GIS can contribute to a circular built environment by creating, visualising, sharing, and analysing spatial data on the location of buildings, components, and materials.
- GIS can help identify where secondary building materials will be available in the future.
- GIS can use spatial statistical methods to identify optimal future locations for circular infrastructure, such as material banks, recycling facilities, or (reverse logistics) hubs for material exchange.
- In combination with digital platforms, GIS can facilitate the tracking and tracing of construction products, components, and materials.
- GIS can help governments prioritise spatial development strategies by highlighting future sites critical to the development of a circular economy.
- GIS data requires strong metadata in order to increase transparency and trustworthiness.

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Tanya Tsui is a PhD candidate at the Faculty of Architecture and the Built Environment in Delft University of Technology. Her research uses urban data science to analyse (waste) material flows to understand the spatial impacts of a circular economy in cities and regions. Her aim is to expand circular cities research beyond the study of governance and material accounting, towards a spatial analysis perspective.

Wendy Wuyts is a researcher at the Norwegian University of Science and Technology (NTNU). She also works as a project manager and consultant for the Norwegian purpose-driven start-up Omtre AS, which is building the first industrial plant for reclaimed timber for the construction sector. Her research focuses on circular economy, sustainable development, political-industrial ecology, and environmental justice. She is involved in the projects SirkTre, circWOOD, and 1-2-Tre-Steg, which aim to foster circular systemic solutions in the timber and architecture, engineering, construction, and deconstruction sector in Norway. She holds a PhD in Environmental Science from Nagoya University, Japan.

Karel Van den Berghe is an assistant professor in Spatial Planning and Urban Development at the Delft University of Technology. His research focuses on the (spatial) circular economy, strategic scenario planning, polycentric economic networks, planning of port cities, Dutch-Belgian cooperation (e.g. Westerschelde), and housing markets. He holds a BSc (2010) and MSc (2012) in geography, an MSc in spatial planning and urbanism (2013), and a PhD in urbanism and spatial planning (2018).