

Article

## GIS and Urban Mining

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**Abstract:** Geographical information systems (GIS) are a kind of location intelligence technology that supports systematic collection, integration, analysis and sharing of spatial data. They provide an effective tool for characterising and visualising geographical distributions of recyclable resources or materials dispersed across urban environments in what may be described as “urban mines”. As logistics can be a key barrier to recycling, GIS are critical for capturing and analysing location intelligence about the distribution and values of recyclable resources and associated collection systems to effectively empower and inform the policy makers and the broader community with comprehensive, accurate and accessible information. This paper reviews the functionality of modern GIS, discusses the potential role of GIS in urban mining studies, and describes how GIS can be used to measure, report, analyse and visualise the spatial or geographical characteristics of dispersed stocks of recyclable waste and their collection and recovery systems. Such information can then be used to model material flows and assess the social and environmental impacts of urban mining. Issues and challenges in the use of GIS for urban mining are also to be addressed.

**Keywords:** urban mining; recyclable resources; material flows; location intelligence; GIS

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### 1. Introduction

Rather than referring to mining in urban areas, urban mining is the process of reclaiming recyclable resources, including compounds and elements, from buildings, urban infrastructure, consumer products and waste dispersed across urban environments [1–4]. More specifically, it involves extracting the precious metals (such as copper, gold and platinum) from urban waste, including electronic waste or e-waste (e.g., old televisions, cell phones and computers). Urban mine stocks are a growing reservoir

of valuable resources and have a tremendous potential for future recycling [1,5]. According to the Australian Bureau of Statistics (ABS), 17 million televisions and 37 million computers had been sent to landfill up to 2008. E-waste is more than 95 percent recyclable. For example, the amount of gold recovered from one tonne of electronic scrap from personal computers is more than that recovered from 17 tonnes of gold ore [6]. However, of the 15.7 million computers that were ready for end of life management in Australia in 2007–2008, only 1.5 million (less than 10%) were recycled. In 2009, the Council of Australian Governments endorsed the National Waste Policy [7]. The policy sets Australia's waste management and resource recovery direction to 2020 in six key areas and identifies 16 priority strategies. One of the key areas is to provide access by decision makers to meaningful, accurate and current national waste and resource recovery data and information to measure progress and educate and inform the behaviour and the choices of the community. Strategy 16 covers the design and development of an online, accessible and up-to-date National Waste Data System (NWDS) for Australia, to support a periodic (three yearly) National Waste Report. NWDS provides statistics of waste and recyclables, as well as household's attitudes and behaviours of recycling [8]. The National Waste Reports provide data on the quantities of waste and recyclables. However, the data and information on where waste and recyclables are located and where electronic appliances reaching the end of their useful life are potentially distributed and geographically concentrated are more important. That is because location-based information or location intelligence about waste and recyclables and their potential stocks and values can help identify actions to build capacity, ensure an appropriate suite of services is available to communities and assist in site selection of waste collection facilities and the recycling industry in order to maximise economic benefits and minimise environmental impacts.

Geographical information systems (GIS) are a proven technology for collecting, managing and analysing location-based data and information and producing location intelligence. Location-based data are also called place-based data, georeferenced data or, more commonly, spatial data. GIS are scale-independent and can be used for examining, exploring and analysing spatial data at global, continental, regional, urban and landscape scales. Therefore, GIS can provide an effective tool for characterising and visualising geographical or spatial distributions of waste and recyclable resources dispersed across urban environments and can be used to capture and analyse location intelligence about the spatial distribution and values of recyclable resources and associated collection systems to effectively empower and inform the policy makers and the broader community with comprehensive, accurate and accessible information. This paper reviews the functionality of modern GIS, examines the potential role of GIS in urban mining, describes how GIS can be used to measure, report, analyse and visualise the spatial or geographical characteristics of dispersed stocks of recyclable waste, and their collection and recovery systems, and discusses the issues and challenges in the use of GIS for urban mining. The discussions are based on a review of significant and representative literature in GIS and urban mining.

## 2. GIS

In general terms, GIS are computer systems for collecting, storing, managing, manipulating, analysing and visualizing geographical or spatial data [9]. They can be considered as “a special case of information systems where the database consists of observations on spatially distributed features,

activities or events, which are defined in space as points, lines, or areas. A GIS manipulates data about these points, lines, and areas to retrieve data for *ad hoc* queries and analyses” [10]. GIS use features to organise, manage and manipulate spatial data. Using a GIS involves capturing the spatial distribution of features by the measurement of the world or of maps. Urban mines, waste collection facilities and the recycling or recovery industry and other related infrastructure are all spatially distributed and, so, can be studied using a GIS.

The functionality of GIS can be described at three levels with an increasing complexity. The first level of functionality is cartographic representation or spatial visualisation. It is the simplest and most basic function of GIS. A map is a basic form of spatial visualisation and representation of spatial data. Maps in GIS are in digital form and called digital maps. A digital map in GIS is a set of data recording the properties or attributes of the features depicted (e.g., stocks of copper, capacity of a waste collection facility, *etc.*) and their geographical locations (often recorded as latitude and longitude, or x, y coordinates in a particular coordinate system). A GIS provides a rich set of map symbols and colours for users to choose to make maps. Map making and geographical analysis are not new, but GIS perform these tasks faster and with more sophistication than do traditional manual methods. Current GIS technology also allows users to make 3D and animated maps.

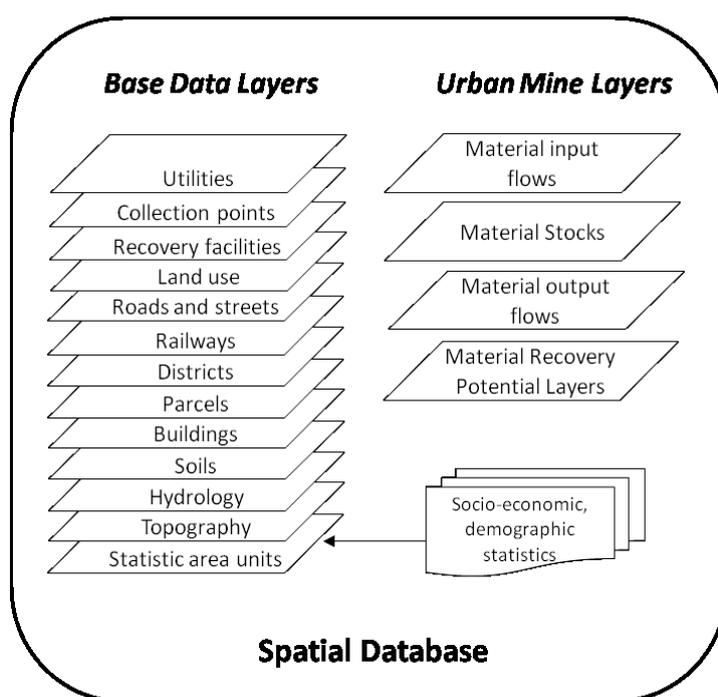
The second level of functionality is spatial data management. Spatial data are typically organised in what is commonly referred to as data layers. A data layer is a digital map of a particular theme. For example, a commonly defined data layer is one containing city streets with pertinent tables of attributes associated with each street. A collection of data layers constitutes a spatial database. Figure 1 shows an example spatial database for urban mining studies. GIS manage a spatial database with specialised database management systems and support a spatial query that retrieves features based on their locations and spatial relationships among the features (e.g., adjacency, inclusion, connectivity and direction). For example, spatial query functions in GIS can be used to search for local government areas (LGA) with more than 5000 kg/km<sup>2</sup> of in-use zinc stock within Victoria State or to find all waste collection facilities within 200 m from highway exits. GIS integrate common database operations, such as a query, and statistical analysis with the unique spatial visualisation and geographical analysis benefits offered by maps.

It is worth noting that data layers in GIS are represented using either a vector data model, in which features are conceptualised as points, lines or areas (polygons) plotted as coordinates in space (*i.e.*, they are defined by their geographical location), or by using a raster data model, in which features are conceptualised as elements of a continuous surface represented by a grid of cells of a particular size (Figure 2). Virtually all modern GIS are able to manipulate both types of data layers, and the choice of vector or raster data model is based on the appropriateness of the model for representing the phenomenon in question and the forms of analysis to which the model is suited.

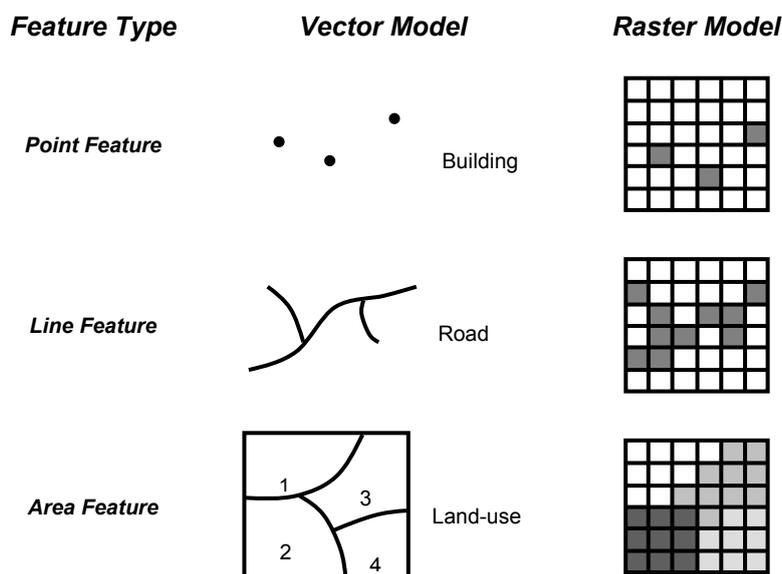
The third level of functionality is spatial analysis and modelling. Spatial analysis and modelling is location based, and the results of spatial analysis are also dependent on the locations of the features being analysed. Spatial analysis and modelling functions in GIS allow users to define and execute spatial and attribute procedures to conduct analysis in space and about place (here, space is regarded largely as a dimension within which matter is located, and a place is a location in space). The functionality of this level is commonly thought of as the heart of a GIS. Generally, GIS provide a large range of analysis capabilities that will be able to operate on the spatial aspects of the spatial data, on

the non-spatial attributes of these data or on both. They range from simple geometric measurements (e.g., measuring shape, area, perimeter and length), proximity analysis (e.g., measuring distance and generating buffer zones of a certain width), network analysis (e.g., calculating distances along transport networks and finding the shortest routes and nearest facilities), spatial statistics (e.g., statistical summaries, spatial clustering and geographically weighted regression analysis) to integrated analysis (e.g., overlay analysis for combining a number of maps and map algebra for implementing mathematical models using maps as input and output variables). These abilities distinguish GIS from other information systems and make them valuable for a wide range of applications, for explaining events, simulating complex processes, predicting outcomes and planning strategies.

**Figure 1.** A spatial database for urban mining studies.



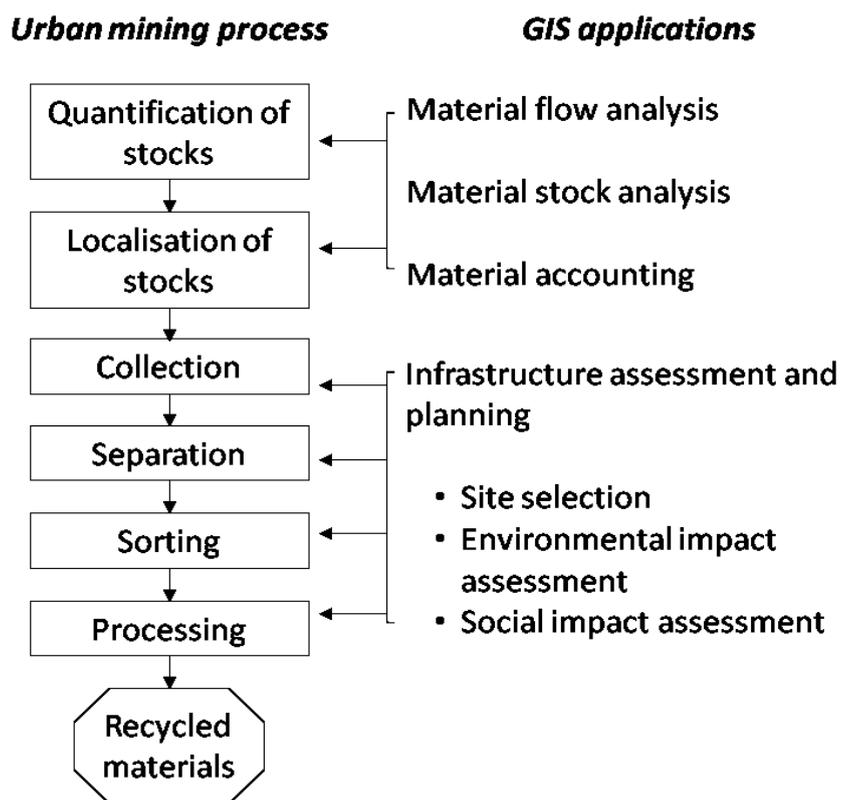
**Figure 2.** Feature types and their representations in two spatial data models.



### 3. GIS in Urban Mining

Urban mining involves material collection, separation, sorting and processing [2]. Collection is essential to success, as it is the first step in recycling. However, collection needs to be based on an understanding of stocks and flows in an urban environment at various levels. GIS can be employed to answer the questions of how much urban mines are present, where the stocks are located and how they are distributed. The answers can be used for evaluation of the economic values of the resources, the social and environmental impacts of mining these resources and the effectiveness of existing and future collection and recovery systems. Figure 3 depicts the major applications of GIS in the urban mining process.

**Figure 3.** Major applications of geographical information systems (GIS) in urban mining.



#### 3.1. Material Flow Analysis

Material flow analysis is used to systematically assess the flows and stocks of materials within a socioeconomic system in a specific geographical area during a particular period of time [11]. It is the first step of every lifecycle assessment for estimating the amount of the resources consumed. According to the first law of thermodynamics (the law of the conservation of mass) [11], total inputs must, by definition, equal total outputs, plus net accumulation of materials in the system. Material flow analysis links the sources, the pathways and the transitional and final sinks of a material. The inflows include extracted or imported materials to be used within the system, and the outflows comprise all materials released to the environment as wastes and those materials that are recycled or exported to outside of the geographical/system boundary. Through balancing inputs and outputs, material flow

analysis identifies the flows of materials and their sources, as well as the accumulation of material stocks during a specific period in time. Material flow analysis is traditionally conducted at the national level. GIS allow for the examination, estimation and prediction of material inflows, outflows and stocks at various levels, from the national to regional and local level. The major role of GIS in material flow analysis is to provide a spatial database and spatial analysis and modelling tools. Particularly, GIS have the ability to integrate data and information from a wide range of sources. For example, GIS enable data and information from one sector (e.g., construction minerals in the building sector) to be combined with data and information from other sectors (e.g., materials in the power grids and consumer goods and those in the transport sector) to provide a comprehensive material accounting (see Section 3.3) in any given area. It also allows the integration of georeferenced building data collected from local governments with construction material intensity data from the building industry to estimate site-specific material stocks by using GIS measurement and statistical summary tools.

Material intensity is often measured as material input per service unit, which is used to quantify the lifecycle-wide requirement of primary materials for products and services [12]. The input of primary raw materials is measured in physical units (kilograms). Material intensity is essentially a function of the type of use, time of use, lifetime of use and geographical location. The data of all these parameters can be stored in a spatial database in GIS. As illustrated in Figure 1, a typical spatial database for material flow analysis in an urban area may comprise base data layers, including street networks, urban district boundaries and different levels of statistical area units, and data layers representing spatial distributions of different types of material uses (such as buildings, power grids, power stations and road networks) at different stages of the lifecycle and their associated properties, as well as socioeconomic and demographic statistics. The material inflow layers can be derived by calculating the material stocks in new uses based on their spatial distribution, size and material intensity and summarised at different levels of statistical area units or to the urban districts. The material outflow layers can be derived by calculating the material stocks in the uses near the end of their lifetime based on their spatial distribution, size, material intensity and material recovery rates, and summarised at different levels of statistical area units or to the urban districts. The material stocks are mainly derived based on the spatial distribution or configuration of the major uses of the subject materials and their material intensities, which is to be discussed in detail in the following section. All the calculations can be conducted in a GIS environment.

With the data on collection and recovery facility locations and their capacities (see Section 3.4) and the spatial distributions of material stocks (see Section 3.2), material flows within waste and resource management systems can be modelled and mapped. In addition, GIS can be used to map material import and export intuitively. Maps can effectively present information in a comprehensive form to decision makers and analysts, who otherwise may not be able to analyse all the data and information from the pages of a tabular report.

### 3.2. Material Stock Analysis

Material stock analysis mainly involves the quantification of stocks of urban mines in a particular form (e.g., in use or hibernation). There are two approaches to material stock analysis: “bottom up” and “top down” [2]. The bottom up approach quantifies material stocks by measuring the stocks

directly. It first identifies the major uses of a given type of materials (e.g., copper), second, determines the material intensity, *i.e.*, the typical amount of the materials in each unit of use (e.g., the amount of copper per metre of a power line), then measures the size of each use (e.g., the total length of the power grid), next calculates the material stock for each type of use and, finally, computes the total stock of the materials in a particular urban area. The top down approach measures the size of the stocks indirectly by examining the inflows and outflows to the stock for a certain period of time or first determining the flows of the material into each major use over a certain period of time and then estimating the material stocks according to the product lifetime. With the top down approach, the estimated material stocks at the national or state level are then scaled down to urban regions on the basis of per capita gross domestic product.

The top-down approach involves scaling down the data at a higher level, which may introduce a lot of uncertainty in terms of spatial distribution. In other words, spatial variations cannot be accurately characterised at a certain level by disaggregating the data at a higher level. Therefore, GIS are not well suited for this approach. However, GIS are well suited for implementing the bottom up approach. Much of the ability of GIS to analyse material stocks with the bottom up approach is founded on their core spatial database, which stores and relates map data within a common spatial framework (*i.e.*, within a specific map projection, like Universal Transverse Mercator/UTM, or a national, regional or locally-defined Euclidean grid system). As discussed above, such a spatial database may contain detailed map data layers describing the spatial distribution, configuration and properties of urban infrastructure (e.g., road and sewer networks), the spatial distribution or configuration of the major uses of the subject materials (such as buildings, power grids, power stations and solar panels) and other socioeconomic and demographic statistical data (e.g., population density, lifestyles, socioeconomic status, *etc.*). After a comprehensive spatial database is built, GIS measurement and statistical tools can be used to spatially calculate and allocate material stocks by combining the content of the subject materials per unit of each use with corresponding spatial information, and spatial visualisation functions are then used to map the spatial distribution of the stocks.

For example, Tanikawa and Hashimoto [1] applied GIS technology to estimate construction material stocks over time with spatio-temporal data. Their study involved the use of a spatial database of an urban area containing spatial data of individual buildings (their locations, shape, area, floor space, structure and material stock per area of building classified by structure), roadways or railways (their locations, structure, length, width and material stock per area of roadway/railway classified by structure) and sewer networks (locations, structure, length, diameter and material stock per length of sewer classified by structure and diameter). They built spatial databases for two urban study areas. Using the spatial databases, they estimated the construction material stocks of buildings, roadways and railways, analysed the spatial distribution and variations of stocked materials, estimated the demolition curve of buildings based on their characteristics at different locations and calculated material accumulation with vertical location, such as materials above and below ground, from the viewpoint of recyclability. The same authors and their research team reported similar work on the estimation of material stocks in buildings and infrastructure in [13–15].

Wallsten *et al.* [3] used GIS to quantify and spatially localise hibernating metal stocks of copper, aluminium and iron (including steel) in infrastructure systems for AC and DC power, telecommunication, town gas and district heating in the city of Norrköping, Sweden. With a spatial

database containing maps representing cables and pipes, as well as buildings, they divided the city into a number of city districts, identified different types of building (older, single-family housing, newer, single-family housing, multi-family housing, industrial and the city centre), estimated metal concentrations per housing unit for each type of building, differentiated the active and inactive infrastructure systems and calculated active and inactive metal stocks for the metals concerned based on information about the copper and aluminum concentrations of the different types of cable (feeder and distribution cables, as well as service and ground wire) and different types of pipes with various diameters and thicknesses. The hibernating metal stocks were summarised in terms of the urban districts and mapped using urban districts as the area unit.

With a similar GIS-based approach, Krook *et al.* [4] used spatial data to characterise the power grids in the cities of Gothenburg and Linköping in Sweden with regard to their total cable length, voltage levels, locations and operational status, estimated in-use and hibernating stocks of copper situated in these local power networks by multiplying the cable length with an average copper concentration and assessed the economic conditions for the recovery of cables in hibernation located in the urban environment.

Van Beers and Graedel [16] took a different approach. They characterised the spatial patterns of the in-use stocks of copper and zinc at four spatial scales (central city, urban region, states/territories and country) using a combination of GIS and exploratory spatial analysis (techniques for describing, discovering and visualising geographical or spatial distributions). The study estimated in-use stocks by deriving suitable average copper and zinc contents for several selected proxy indicators (including the type of buildings, the number of motor vehicles, the length of electrified railway track, the household income, *etc.*), multiplying these factors by the quantities of the proxy indicators within a geographical area of interest and aggregating the results. The proxy data are spatially distributed, and they were mainly derived from the Australian census data. In this study, the in-use copper and zinc stocks were investigated in more than thirty four thousand census collection districts, about six hundred local governmental areas and eight states/territories. Maps were produced with GIS to show how the densities of the in-use stocks at one spatial level manifest themselves at higher spatial levels. Compared with the studies by Wallsten *et al.* [3] and Tanikawa and Hashimoto [1], van Beers and Graedel [16] mainly relied on area aggregated statistical data, literature review, personal communication, informed estimates and empirical models, rather than on a detailed spatial database containing spatial distributions and configurations of the urban elements stocked with the materials under investigation. Their results are less accurate, having the accumulated uncertainties of about 40% for copper and  $-40\%/+50\%$  for zinc of the estimated total stocks. Nevertheless, they provide useful information for identifying high spatial density areas for recovering and reusing metals in Australia. Their research also highlights the importance of a comprehensive and detailed spatial database and selection of appropriate proxy indicators for accurate material stock analysis.

Van Beers and Graedel [17] also quantified and mapped end-of-life flows of copper and zinc in Australia at the level of local government areas, based on existing and anticipated in-use stocks, their residence times and their historical and anticipated future evolution. The research demonstrated that the integration of GIS with material stock analysis enabled the comparison of end-of-life copper and zinc in geographical areas with different demographic and industrial characteristics and provided useful information for the optimization of copper and zinc recycling.

### 3.3. Material Accounting

Material accounting is the regular updating of the measurements of the key flows and stocks resulting from material flow analysis. GIS can be used to build a material accounting system, which records, produces, updates and manages data about material flows, stocks and concentrations in a particular urban area and allows the analysis of spatio-temporal changes in material stocks (in terms of the mass of the stock, as well as the rate of change of the stock per unit time) and the detection and prediction of trends. The data acquisition, storage, retrieval and management functions of GIS allow systematic accounting of all materials crossing sector and/or geographical boundaries. Such a material accounting system can be updated constantly, and statistical summaries and maps can be made instantly.

To date, there has been no reported material accounting system built and maintained using GIS technology. Indeed, a GIS-based material accounting system will be able to integrate data on urban infrastructure, urban land use and spatial patterns of various uses of different types of materials. When changes occur in the magnitude and spatial pattern of one or more uses of a particular type of material, the accounting system may re-calculate the material inputs, outputs and stocks and update the database automatically. It will also allow for allocating material flow and land use data to economic sectors and analysing the resource and land use intensities of different economic activities simultaneously to establish the relation between material flows and land uses. Therefore, a GIS-based material accounting system will present an opportunity to study the spatial distribution of material flows and the implications of changes in the metabolic profile of urban areas for urban land use changes and to utilise land use intensity (e.g., building density, road density or the concentration of other land use activities in an area) as a criterion to evaluate different types of material flows.

### 3.4. Infrastructure Assessment and Planning for Urban Mining

Collection and recovery are vital to the success of urban mining. It is important to proactively consider how the recyclable materials stocked in an urban environment are managed once they reach the end of their life span. The infrastructure for urban mining mainly encompasses the collection or transfer stations, landfills and recycling or recovery facilities. To implement an efficient and sustainable recovery system for materials, such as from e-waste, requires adequate capabilities for collection, recovery, recycling and refining and sufficient control over their material quality and the environmental and social impacts of the related processes. It may involve answering the following questions:

- Where is the existing infrastructure for collection and recovery distributed?
- To what extent is the existing infrastructure utilised and how can it be optimised?
- Is new infrastructure required?
- Where will new infrastructure be deployed?
- What are the environmental, social and economic impacts of the infrastructure and its operations?

GIS can be applied to address these questions. Data on the current collection and recovery infrastructure (including operators, regulatory and planning status, capacities, types of processes and wastes processed, types of transport and cost information), together with the material stocks and their spatial distribution data derived from material stock analysis, can be compiled into a spatial database

managed in a GIS and analysed using spatial analysis functions, including proximity analysis, network analysis and location allocation modelling. In general, material stock and flow analysis should precede the planning of the collection and recycling facilities. Distance measurement is basic in the spatial analysis of infrastructure for urban mining. From a waste collection perspective, a longer distance between stocks and collection and recovery facilities means a less likely recovery, due to increased transport cost. On the other hand, distance from collection and recovery sites to communities is one of the indicators of how vulnerable the communities are to possible toxic material leaching.

For example, Goe *et al.* [18] applied GIS to analyse infrastructure for recycling solar photovoltaics (PV) materials in New York State, USA. They collected PV installation and recovery infrastructure data. PV installation data are point data recording PV panel locations, capacities and costs. By using spatial interpolation techniques in GIS, a heat map was produced based on the PV installation point data to show the likely PV installations (used as a proxy indicator of potential stocks of solar panel waste) at every location in the state. The map was then compared to the spatial distribution of the current recovery infrastructure to identify the locations with high potential that are far away from recovery facilities. The map could also be used to estimate how much material would potentially need to be handled at the collection recovery facilities. To further assess the existing collection and recovery infrastructure, the study calculated the collection route distance between each PV installation site and the collection and recovery points along the transport network using the network analysis functions in GIS and developed an optimisation model constrained by PV material stock, facility cost, capacity and collection route distances to minimise cost. The model was used to assess whether the existing collection and recovery infrastructure could, at a minimal cost, achieve collection and recovery at or above municipal solid waste recycling rates for all PV wastes. It also built a site selection model using overlay analysis functions in GIS to identify suitable sites for new collection and recovery facilities based on multiple criteria, including land use, elevation, population and distance from communities, schools and wetlands (all represented in data layers in the spatial database) in order to minimise potential negative environmental and social impacts. The collection route distances from the newly identified collection and recovery facilities were computed and fed into the optimisation model to determine which of these new facilities would be part of a minimum cost system of solar panel recovery. This study demonstrated how GIS can be used to estimate potential stocks, assess the environmental, social and economic implications of the existing infrastructure for collection and recovery and to plan new infrastructure to meet future demand.

#### **4. Conclusions: Issues and Challenges**

This paper provides an overview of the applicability of GIS to urban mining. GIS offers a useful platform for data management, visualisation and analysis of the spatial patterns and relationships that comprise the basic datasets used in some urban mining studies. Although urban mining has many issues related to spatial analysis, GIS applications in urban mining have been largely focused on material stock analysis and infrastructure planning. One of the key issues is the data accessibility. At the national level, some data on recyclable wastes can be obtained directly from statistical bureaus in published form. Almost all material input and trade data in physical units are accessible. However, at the regional and urban level, data accessibility is limited. Data are generally dispersed among several

organisations and firms. They may be commercial-in-confidence, such as mobile phone sale data and utility network data. It is expected that the sources of data for urban mining studies will be different across institutions. This may make it difficult to produce a consistent urban-wide set of data sources and methods.

The second issue is the data availability. Many data required may not be available. Industrial wastes often contain specialized materials and are one of the major waste streams with high recycling rates. They are an important component of potential urban mines. However, there is generally no single, definitive, national information source on industrial wastes. The data about industrial wastes are patchy. The estimated quantity of recyclable wastes reported by a range of agencies, including various industry information sources, often tells us little about who is generating which wastes and in which parts of the country. It is also very challenging to study the spatially distributed magnitude and flow of e-waste at the urban scale, as the relevant data are often unavailable, or incomplete or incommensurable. For example, electronic items, such as mobile phones and TV sets, may transfer from first users to second-hand users or may be traded in when purchasing a new item from a retailer. Sometimes, they are disposed together with municipal solid waste to landfills. The average life of these items is also not static. In other words, electronic items bought in one particular year would not necessarily become obsolete at the end of the average lifecycle, depending on the usage of the devices and the changes and innovation of technology. There is a need to have an effective and efficient method to track flows of such electronic items until they reach their end-of-life or end-of-use. So far, there has been no reported study on the spatial analysis of e-waste using GIS.

In addition, data may not be available in physical units for a number of material flows and, therefore, may have to be estimated from more general data (e.g., load volume data and sales data). This is particularly so for wastes generated by consumers. An approach to overcome this knowledge gap may be to study individual consumers and examine their spatio-temporal consumption pattern based on socioeconomic variables, such as population, households, mobility, employment, lifestyle, income and floor space. This attempts to account for consumption patterns on the basis of the impact of final demand for consumer goods and services [19]. By relating the spatio-temporal consumption pattern to the demand for consumer goods and services, the potential material stocks and flows may be estimated at a spatially disaggregated level. Spatial disaggregation is downscaling. It is the process by which information at a coarse spatial scale is translated to finer scales, while maintaining consistency with the original dataset.

To address the data issues, a specific national spatial data infrastructure should be built to support urban mining. As discussed above, spatial data on material stocks and flows and infrastructure are dispersed and fragmented. They may be inconsistent in terms of data formats, data items, measurement units and geographical scales. These problems make it difficult to identify, access and to use available data from different sources. Spatial data infrastructure delivers to users integrated spatial information services. These services should allow for identifying and accessing spatial data for urban mining studies from a wide range of sources in an interoperable way for a variety of uses. A common framework of standards and tools based on these standards needs to be developed to maximise the use of the total available resources for spatial data infrastructure through cooperation among stakeholders concerning urban mining.

A recyclable resource GIS is recommended, which can provide a spatial database supported by a national spatial data infrastructure and analytical functions for urban mining studies, as well as tools for effectively communicating the values of recyclable resources to the broader community. A web mapping portal interfaced to the recyclable resource GIS is a particularly powerful medium for engaging with stakeholders and the general public. Access to meaningful, accurate and current waste and resource recovery data and information can increase capacity in communities to manage waste and recover and reuse resources. GIS can be used to help provide such information.

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### Conflicts of Interest

The author declares no conflict of interest.

### References

1. Tanikawa, H.; Hashimoto, S. Urban stock over time: Spatial material stock analysis using 4d-GIS. *Build. Res. Inf.* **2009**, *37*, 483–502.
2. Graedel, T.E. The prospects for urban mining. *Bridge* **2011**, *41*, 43–50.
3. Wallsten, B.; Carlsson, A.; Frändegård, P.; Krook, J.; Svanström, S. To prospect an urban mine—Assessing the metal recovery potential of infrastructure “cold spots” in Norrköping, Sweden. *J. Clean. Prod.* **2013**, *55*, 103–111.
4. Krook, J.; Carlsson, A.; Eklund, M.; Frändegård, A.; Svensson, N. Urban mining: Hibernating copper stocks in local power grids. *J. Clean. Prod.* **2011**, *19*, 1052–1056.
5. Wallsten, B.; Johansson, N.; Krook, J. A cable laid is a cable played: On the hibernation logic behind urban infrastructure mines. *J. Urban Technol.* **2013**, *20*, 85–103.
6. Electronics TakeBack Coalition. Facts and Figures on E-Waste and Recycling 2013. Available online: [http://www.electronicstakeback.com/wp-content/uploads/Facts\\_and\\_Figures](http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures). (accessed on 5 November 2013).
7. Department of the Environment, Water, Heritage and the Arts (DEWHA). *National Waste Policy: Less Waste, More Resources*; DEWHA, the Australian Government: Canberra, Australia, 2009.
8. Department of Sustainability, Environment, Water, Population and Communities (DSEWPC). *National Waste Data System: System Summaries—ABS Waste and Recycling Data*; DSEWPC, the Australian Government: Canberra, Australia, 2012.
9. Chang, K.T. *Introduction to Geographic Information Systems*, 7th ed; McGraw-Hill: New York, NY, USA, 2014.
10. Dueker, K.J. Land resource information systems: A review of fifteen years’ experience. *Geo Proc.* **1979**, *1*, 105–128.
11. Brunner, P.H.; Rechberger, H. *Handbook of Material Flow Analysis*; The CRC Press: Boca Raton, FL, USA, 2003.

12. Bringezu, S.; Stiller, H.; Schmidt-Bleek, F. Material intensity analysis—A screening step of LCA. In Proceedings of the Second International Conference on EcoBalance, Tsukuba, Japan, 18–20 November 1996; pp.147–152.
13. Tanikawa, H.; Hashimoto, S.; Moriguchi, Y. Estimation of material stock in urban civil infrastructures and buildings for the prediction of waste generation. In Proceedings of the Fifth International Conference on Ecobalance, Tsukuba, Japan, 6–8 November 2002. Available online: [http://hosting.creativeconcern.com/ecoregion/downloads/workingpapers/2002Ecobalance\\_tanikawa.pdf](http://hosting.creativeconcern.com/ecoregion/downloads/workingpapers/2002Ecobalance_tanikawa.pdf) (accessed on 22 February 2014).
14. Tanikawa, H.; Sakamoto, T.; Hashimoto, S.; Moriguchi, Y. Visualization of regional material flow using over-flow potential maps. In Proceedings of Gordon Research Conference, Industry Ecology, Oxford, UK, 1–6 August 2004; The Queen’s College: Oxford, UK. Available online: [http://hosting.creativeconcern.com/ecoregion/downloads/workingpapers/2004Ecobalance\\_tanikawa.pdf](http://hosting.creativeconcern.com/ecoregion/downloads/workingpapers/2004Ecobalance_tanikawa.pdf) (accessed on 22 February 2014).
15. Tanikawa, H.; Inazu, R.; Hashimoto, S.; Kaneko, S. Estimation of historical/spatial changes in subsurface material stock related to the construction sector of urban areas in Japan. In *From Headwaters to the Ocean: Hydrological Change and Watershed Management*; Taniguchi, M., Burnett, W.C., Fukushima, Y., Haigh, M., Umezawa, Y., Eds.; CRC Press: Leiden, the Netherlands, 2008; pp. 591–597.
16. Van Beers, D.; Graedel, T.E. Spatial characterisation of multi-level in-use copper and zinc stocks in Australia. *J. Clean. Prod.* **2007**, *15*, 849–861.
17. Van Beers, D.; Graedel, T.E. Copper and zinc recycling in Australia: Potential quantities and policy options. *J. Clean. Prod.* **2007**, *15*, 862–877.
18. Goe, M.; Tomaszewski, B.; Gaustad, G. Infrastructure planning for solar technology recycling. *ArcUser* **2013**, *16*, 20–23.
19. Sinclair, P.; Papathanasopoulou, E.; Meller, W.; Jackson, T. Towards an integrated regional materials flow accounting model. *J. Ind. Ecol.* **2005**, *9*, 69–84.

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