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A review of possibilities and limitations

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DOI
10.1016/j.resconrec.2018.06.024

Publication date
2018

Document Version
Final published version

Published in
Resources, Conservation and Recycling

Resources, Conservation & Recycling 138 (2018) 32–39

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Urban mining and buildings: A review of possibilities and limitations

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ARTICLE INFO

Keywords:
Urban mining
Buildings
Construction and demolition waste
Renovation
BIM (Building Information Modelling)

ABSTRACT

In recent years there has been growing interest in urban mining in buildings from various environmental and economic perspectives. Materials hidden in buildings are attractive alternatives to raw ones and building activities are responsible for a large share of urban waste in many societies. The paper presents an analysis of possibilities for urban mining in Amsterdam, initially focused on metals in residential buildings. Both global literature and local analysis suggest that performance in resource recovery from buildings is already as high as it can get. However, estimation of material content in buildings and of waste processing rates is far from reliable, accurate and precise enough to support such claims or identify possibilities for further improvement, including localization of resources in buildings and connections to building activities, in particular renovation.

1. Introduction

The paper presents the findings of a study on the feasibility of urban mining (UM), initially focused on metals in residential buildings in the city of Amsterdam. It addresses the availability of valuable resources in the built environment as well as the possibilities for their recovery, including the current performance in construction and demolition waste (C&DW) processing. The focus on metals was motivated by current high prices and demand, which make metals attractive targets for all parties involved in C&DW. UM for metals could therefore be considered as an opportune starting point for explorations of potential, as well as for UM deployment in general.

Residential buildings may have smaller sizes, distributed ownership, smaller volume per unit, longer life than industrial or office buildings and a greater variety of materials (Schebek et al., 2017) but in terms of overall building stock, housing is the vast majority: in February 2018 there were 7.746.202 residential properties versus 1.128.965 non-residential ones in the Netherlands (CBS, 2018). Moreover, the way Dutch housing is organized and the high repetition and standardization that characterizes it, are particularly relevant for UM, as they promise structural, regular opportunities.

The findings are considered from the viewpoint of AECO (architecture, engineering, construction and operation of buildings): the disciplines involved in the production and management of the built environment, which could therefore contribute actively to UM. With the recent societal emphasis on circularity, UM connects to the processes of AECO and the information produced and managed by AECO, in particular in the operation stage (up to and including demolition), i.e. with respect to the existing building stock.

The study comprised three main parts:

1 Exploratory literature review of the global state of the art with respect to the estimation of metal content in residential buildings, possibilities for their recovery and measures of current performance in C&DW processing. Particular attention was given to papers that included actual cases as sources of quantitative information, so as to establish a reliable picture of what is available and how it is currently processed.
2 Analysis of local practices, experiences and performance, based on official statistics and semi-structured interviews with Dutch experts in building demolition and waste management. The comparison of local conditions to the literature review aimed at identifying local factors that could stimulate or may limit UM.
3 Evaluation of the utility and applicability of literature review results to the particular context of Amsterdam and the Netherlands:
   a Estimation of resources available in existing building stock
   b Identification of opportunities for the recovery of these resources
   c What is already happening in C&DW processing; possible room for improvement or additional UM activities

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https://doi.org/10.1016/j.resconrec.2018.06.024
Received 2 April 2018; Received in revised form 26 June 2018; Accepted 26 June 2018

1.1. Urban mining

In recent years, increased demand for many materials and concerns for the effects of waste have stimulated interest in UM from various perspectives, environmental and economic. As concentrations of elements in anthropogenic stocks are often comparable or even higher than natural stocks (Cossu and Williams, 2015), recovering resources from the anthroposphere is an attractive alternative to depleting natural ones, incurring high costs for extraction and transport from primary sources or becoming dependent on those who control the primary sources. The promise seems substantial and widely accepted, concerning not only household waste and end-of-life products like vehicles or electrical and equipment waste (WEEE) but also the built environment, since construction is both a major user of materials and a primary producer of waste (Agamuthu, 2008; Li, 2015).

Although UM originally focused on WEEE, it is increasingly seen as cumulatively and rather indiscriminately applicable to all kinds of waste, produced from various aspects of urban life, despite marked differences between these aspects and resulting kinds of waste or waste processing. Such differences can be critical for UM, e.g. with respect to the lifespan of products and their vitality for human activities while in use. Additionally, UM often focuses on what happens after extraction from the anthroposphere. Availability and improvement of collection rates are also considered but practical and technical issues in pre-processing and physical separation from the environment less so (Tesfaye et al., 2017). In short, UM seems to depart less from resource efficiency (Xue et al., 2017) and more from waste processing of typical urban waste kinds, often as a strategic component of circularity or sustainability (Arora et al., 2017; Cheng et al., 2018).

1.2. Buildings as mines

Buildings have an uneasy fit in the UM framework. This is a reflection of the distinction between two main kinds of resources in UM, stock and flow resources (Cossu and Williams, 2015), the apparent orientation of UM towards the latter and of particular characteristics of building stocks. The lifespan of building components is not only significantly longer to that of e.g. electronic equipment but also quite varied, depending on material, subsystem (e.g. heating, plumbing, electrical or loadbearing), use intensity and weathering. Some analyses suggest that as little as 3% of materials may be extractable from buildings and then only after a protracted lifespan – buildings actually extend the in-use life of many materials (Ciacci et al., 2017; Lederer et al., 2016). This relates to a number of factors particular to buildings, including:

- Buildings are critical and dominant parts of our habitat. We need the protection and comfort they offer and are reluctant to reduce them: the price of scrap steel has to become too high to make one consider relinquishing the central heating pipes and radiators of their homes or offices without a heating alternative.
- The importance of buildings goes beyond practical needs and extends to cultural aspects of society, as evidenced by the large number of listed buildings in many countries.
- Buildings tend to become vintage rather than old, in the sense that they lose little if any value over time. On the contrary, the preeminence of factors like location and the overall similarity in performance between new and older buildings make the value of old buildings often rise together with the price of new ones (Clapp and Salavei, 2010; Coulson and McMillen, 2008; Syed and De Haan, 2017). This too stimulates preservation and maintenance of buildings beyond their assumed functional or technical lifespan.
- As buildings are maintained for quite long periods, they are frequently adapted: their original structure and composition may change substantially and include new materials or subsystems following changes in architectural approach, technology or user requirements, like having central heating in medieval buildings (Grussing, 2014; Méquignon and Ait Haddou, 2014; Struhala and Stranska, 2016). It is often hard to know which resources one might find in a building without extensive research – unlike e.g. household appliances, which may change little even after many repairs.
- Ownership, operational and economic management of buildings is widely distributed and largely uncoordinated, in contrast to other stocks in the built environment like roads and utilities (infrastructure).

In conclusion, buildings may superficially seem to comprise composite waste, in a manner typical of urban mines, but this is merely a picture that emerges from old-fashioned, indiscriminate demolition practices. It is a view that reduces the built environment to rubble prior to considering it as a subject for UM and restricts UM to what takes place after collection, similarly to e.g. WEEE (Arora et al., 2017; Coelho and de Brito, 2013b). It neither acknowledges the habitation function of buildings nor takes into account the structured manner by which materials are organized into building components and elements. This structure determines extraction ease and collection availability, since it is building components that usually turn from in-use to end-of-life products, generally in relation to changes in primary functions, e.g. transition to a different heating system.

1.3. Cities as mines

Recovering resources from the anthroposphere in a densely populated city is a complex task, nevertheless justified by the joint imperative of reducing unprocessed waste and extracting value from existing stocks and flows. Moreover, cities seem to be the right place for it: the larger the size of a community, the higher the building and demolition activity (Huuhka and Lahdensivu, 2016). Waste generation rates (WGR) for C&DW are also higher in countries with higher population densities (Bertram et al., 2002). The underlying reasons include higher economic activity, population mobility, higher living standards and stricter environmental regulations – all characteristic of old yet still dynamic urban centres like Amsterdam. This has not escaped the attention of local authorities: in common with other Dutch cities, Amsterdam has embraced the circular economy concept, developed white papers stating ambitions linked to national policies and established platforms where public and private forerunners as well as knowledge institutes meet to promote circularity (Gemeente_Amsterdam, 2014).

2. Literature review

2.1. Construction and demolition waste

Construction and demolition (C&D) are widely acknowledged as one of the most important sources of waste. C&DW in the Netherlands in 2010 (a lean year for the building industry) amounted to 24 Mt, while industry produced 15 Mt and consumers 9 Mt (Rijkswaterstaat_Leefomgeving, 2013). C&DW is generally divided by its cause: new construction, renovation and demolition. Demolition contributes up to 70% of C&DW in some contexts (Wu et al., 2016). In others it is calculated at 55%, with renovation producing 29% and new construction 16%, while demolition is 8% of the total building activity, renovation 40% and new construction 52% (Bergsdal et al., 2007). Waste generation per gross floor area (WGA) at demolition is reported as being twenty (Bergsdal et al., 2007) or even fifty times more than new construction (Wu et al., 2016). Finally, renovation WGA is estimated at five times more than new construction (Bergsdal et al., 2007). These numbers illustrate the quantitative potential of C&DW and suggest that demolition dominates its production, although renovation also warrants attention.

2.2. Metals from buildings

Given the high prices for metals in the recent past, interest in recycling metals from waste is hardly surprising. Already 30% of copper consumed in Europe and 50% of iron in the USA originates from secondary sources (Klinglmair and Fellner, 2010), while in Australia 65% of steel is recycled, including upscaling of old cast iron (Ness et al., 2015). Ambitions for the future remain high: copper, iron, aluminium and lead substitution rates (replacement of primary metal sources by secondary ones) through UM in China can be up to 50% by 2030 (Wang et al., 2015; Wen et al., 2015). Recycling of metals is also significant within the waste industry itself because it greatly reduces its net carbon footprint (Kucukvar et al., 2016).

With the worldwide popularity of reinforced concrete as building material and the increasing quantities of wiring and piping in buildings, it is even less surprising that buildings contain 50% or possibly more of all metals in use (van Beers and Graedel, 2007). This makes C&DW important in comparison to other sources. For copper recovery it is one of the most promising sources, together with WEEE (the clear leader) and end-of-life vehicles; especially in terms of mass flow, it competes with industrial and municipal solid waste (Bertram et al., 2002). Metals represent 3% of all C&DW mass according to most sources (Bertram et al., 2002; Cochran et al., 2007), although some estimates go up to 13,5% (Dahlbo et al., 2015) – something that can be attributed not only to regional differences and variety in construction types but also to how waste generation is estimated (discussed further below). Distinction between types of C&D is also important: renovation may produce eight times more metal waste than new construction, while demolition goes up to eighty times more, as metals integrated in a building are released (Bergsdal et al., 2007). Unsurprisingly, these numbers support the potential of C&DW and the significance of demolition and renovation also for metal recovery.

2.3. Recycling performance

The combination of high metal prices, the theoretical 100% recyclability of metals, their potentially endless lifecycle and high efficiency of separation from other waste, in combination with measures like high municipal tariffs or landfill bans for recyclable waste, raise expectations: 100% recycling of metals is a key goal in the global C&DW industry (Kucukvar et al., 2016). Of metals embedded in concrete, 90% is expected to be recovered and recycled (Wang et al., 2015).

Such expectations are not out of tone with recycling performance in C&D: annually 94% of C&DW in the Netherlands is successfully recycled (Rijkswaterstaat_Leefomgeving, 2013), albeit mostly in downgraded forms, e.g. as materials for road building (Mulder et al., 2007). By comparison, the target set by the European Commission for 2020 is 70% recycling of C&DW (Directive, 2008). Metal recycling is a major contributor to this success: it performs so well that assessments of C&DW management suggest that further improvement is not expected to have an effect on overall performance (Cheng and Ma, 2013; Dahlbo et al., 2015).

2.4. Estimation approaches

The impressive numbers found in UM and C&DW literature necessitate a closer examination of how they are calculated. There are two main approaches to estimating the quantities and composition of metals in use (Drakonakis et al., 2007):

1 *Top down:* estimations from the balance between the amount of metals entering use and the amount of metals exiting use in end-of-life products or other waste. This approach requires reliable data over several decades. Top-down approaches are popular with flow resources (Cheng et al., 2018).
2 *Bottom up:* estimations based on inventories of all metal products in use and the application of proxy indicators to cover gaps and simplify counting. This approach is popular with stock resources (Cheng et al., 2018), because of the availability of data on proxy indicators like buildings or motor vehicles (van Beers and Graedel, 2007). The main problem lies in the reliability of estimating the metal composition of such indicators (Ortlepp et al., 2015).

Both approaches seem to have difficulty in finding the right data. Bottom-up approaches tend to use rather abstract features such as the period of construction or building height (Kleemann et al., 2017; Mercader-Moyano and Ramírez-de-Arellano-Agudo, 2013; Oezdemir et al., 2017; Ortlepp et al., 2016; Schebek et al., 2017) or data from processes like transport (Mah et al., 2016). For the metal content of buildings, relations with such features are determined in a number of complementary manners, including rules of thumb in construction textbooks, site visits, lifetime analyses, end-of-life building inspections prior to demolition, and comparisons to precedents (Wittmer et al., 2007; Wu et al., 2014).

A key problem with such estimates is generalization: what holds for one building may not apply to another, unlike e.g. motor vehicles, because buildings are seldom mass produced in an industrialized manner (Gerst and Graedel, 2008). The usual solution is definition of types at high abstraction levels: C&DW literature abounds with generic categories like residential versus non-residential or small versus large buildings. The most useful categorizations involve basic features like the type of load-bearing structure (steel frame, reinforced concrete, wood frame etc.), which bear on the material composition of a building. As a result, literature contains a wide range of various estimates for the metal content of residential buildings (Table 1):

Probably the best illustration of fuzziness in estimates is a comparison between the results of a study on a number of German buildings with the results of precedent research, i.e. for rather similar samples (Kleemann et al., 2016):

Table 1
Estimates for the metal content of residential buildings.

Place	Metal	Subsystem	Estimate	Unit	Remarks	Source
New Haven, CT	Copper	Air conditioning and refrigeration	3.1	Kg/c	USA average: 16	(Drakonakis et al., 2007)
Australia	Copper	All	110 / 195	Dwelling	In shared living complex / single family house	(van Beers and Graedel, 2007)
Switzerland	Copper	Other than roof or wiring	24	Kg/c		(Wittmer and Lichtensteiger, 2007)
New Haven, CT	Copper	Plumbing	28	Kg/c	USA average: 32	(Drakonakis et al., 2007)
Cape Town	Copper	Plumbing	1.3-2.7	Kg/c		(Wittmer and Lichtensteiger, 2007)
Switzerland	Copper	Roof	32	Kg/c		(Wittmer and Lichtensteiger, 2007)
Switzerland	Copper	Wiring	24	Kg/c		(Wittmer and Lichtensteiger, 2007)
Cape Town	Copper	Wiring	2.7-5.3	Kg/c		(Wittmer and Lichtensteiger, 2007)
New Haven, CT	Copper	Wiring	25	Kg/c	USA average: 28	(Drakonakis et al., 2007)
New Haven, CT	Steel	All	606	Kg/c		(Drakonakis et al., 2007)
China	Steel	All	14-75	kg/m^2	depending on period and type of construction	(Huang et al., 2013)
Australia	Zinc	All	188 / 290	Dwelling	In shared living complex / single family house	(van Beers and Graedel, 2007)

Table 2
Metal WGA estimate comparison.

Place	Metal	Activity	Estimate	Unit	Remarks	Source
Florida	All	Construction	0.3 / 1.5	kg/m^2	Wood frame / concrete	(Cochran et al., 2007)
EU	All	Construction	0.9-3.9	kg/m^2		(Mália et al., 2013)
Florida	All	Demolition	10 / 15	kg/m^2	Wood frame / concrete	(Cochran et al., 2007)
EU	All	Demolition	9.8-28.4	kg/m^2		(Mália et al., 2013)
Florida	All	Renovation	0.75	kg/m^2	Wood frame / concrete	(Cochran et al., 2007)
EU	All	Renovation	0.4-6.8	kg/m^2		(Mália et al., 2013)
Florida	All	Roof replacement	6.8	kg/m^2		(Cochran et al., 2007)
China	Steel	Construction	4	kg/m^2		(Li et al., 2013)
China	Steel	Construction	5.1	kg/m^2	According to transportation records	(Li et al., 2013)
China	Steel	Construction	6	kg/m^2	Other sources	(Li et al., 2013)
USA	Steel	Construction	0.9	kg/m^2		(Li et al., 2013)
Norway	Steel	Construction	0.48	kg/m^2		(Li et al., 2013)
Korea	Steel	Construction	4.53	kg/m^2		(Li et al., 2013)

- steel: study 0,1–8,6 kg/m^3 – others 2,08-37
- aluminium: study 0,03–0,5 kg/m^3 – others 0,013
- copper: study 0,002–0,5 kg/m^3 – others 0,05-0,24

In terms of WGA, similar variation can be observed for metals (Table 2):

2.5. Processing

A number of studies deals not only with what and how much but also with how C&DW can be processed (Kleemann et al., 2017). The location of C&DW processing seems critical with respect to volume, availability, transport and other factors (Coelho and de Brito, 2013b; Ulubeyli et al., 2017; Xue et al., 2017). On-site processing is deemed generally difficult and expensive (Ulubeyli et al., 2017), leading to the assumption that C&DW processing starts at plant (Coelho and de Brito, 2013b). Still, there is growing interest in mobile processing plants (Ulubeyli et al., 2017; Zhao et al., 2010), which link UM to pre-processing and separation on site (Tesfaye et al., 2017), as well as to deconstruction, which under such conditions emerges as a viable alternative to demolition (Coelho and de Brito, 2011, 2013a; Mulder et al., 2007) and extends UM to circularity forms other than mere recycling, like re-use and re-manufacturing (Akanbi et al., 2018; Eames et al., 2013). It also offers possibilities for connections with AECO processes in the lifecycle of buildings, for example using building vacancy as trigger for UM (Huuhka, 2016). As discussed below, such connections are significant for both propagating and scoping UM in buildings.

3. Local conditions

The branch organization of demolition and C&DW processing firms in the Netherlands estimates that about 40% of waste in the Netherlands is generated by the C&D industry, making C&DW the largest part of waste in the country. 90% of the total C&DW weight is concrete, brick or asphalt and 10% contains plastics, wood and metals (Vereniging_Afvalbedrijven, 2015). Motivated by ease of extraction, value, regulations and social involvement, metals appear to be in a closed-loop waste system (Vereniging_Afvalbedrijven, 2013). As a valuable commodity, they receive particular attention, even in residential buildings where the concentration of metals is lower than in non-residential ones.

In order to validate the results of the literature review and the above claims on C&DW from Dutch buildings, six demolition and C&DW experts were interviewed (see Appendix). The semi-structured interviews also provided insights into the processes of identification, extraction and processing of metal components, and on the role of building information in these processes.

Estimates of metal quantities by the interviewed specialists varied from 5 m^3 of iron (primarily heating services and construction steel) and 1,5 m^3 of all other metals to 150 kg of ferrous metals per single-family house. It should be noted that such empirical estimates tended to be on the conservative side (so as to take performance-reducing risks into account) and that they are bounded by the extraction process: they stress components and materials that can be extracted directly on site.

Concerning performance, the interviews suggest that metals are practically always recovered at some point in the processing chain and mostly recycled. In demolition, metals present in a building are identified by visual inspection beforehand, mostly on the basis of experience and expertise. Building documentation is rarely if ever used on site. Pre- and postvisiting analyses and planning may involve building drawings, mostly as a general reference frame, e.g. for the calculation of total building volumes or site management. Demolition experts appear to be experts in value recognition, too: they are aware of the potential value of materials in general and often of particular materials and components to specific potential buyers (in which cases deconstruction is an attractive option). Demolition firms are well connected and capable of even anticipating market demand for materials from secondary sources.

In terms of process, most of the easy-to-remove metal components have to be extracted quickly by demolition workers before petty criminals may interfere. Pipes, wires, radiators etc. are often removed by hand from walls. Depending on the time frame of the project, the experience of the demolition firm and current demand, the harder-to-reach metal components may also be extracted on site. When time or experience is limited or demand lags behind, mixed waste is delivered to waste processing facilities and metals are extracted off site.

Demolition and waste processing experts are also cognizant of risks and dangers, in particular pollutants that may render C&DW recycling unfeasible. In the Netherlands, this primarily refers to asbestos, which can be present in piping, plating (especially around heating boilers), façade elements and, most disturbingly for metal recovery, pastes and sealants. Proximity to asbestos means that metal components are currently excluded from further processing, at least until decontamination.

Waste separation at the source, as required by Dutch national building regulations (Ministerie_van_Binnenlandse_Zaken_en_Koninkrijksrelaties, 2012), mainly concerns hazardous substances but C&DW firms appear willing to go beyond their legal obligations. In the case of metals, there is a clear financial drive but corporate responsibility, including environmental awareness, is also becoming a factor. Some demolition firms initiate far-reaching agreements with manufacturers concerning direct re-entry of specific C&DW in production processes, so as to reduce the need for materials from primary sources.

The overall chain seems highly variable and dependent on time, opportunity and personal preferences but in terms of recovery interviewees thought there was little improvement possible. The industry appears aware of opportunities, skilled and knowledgeable. What seems variable and ad hoc could also be viewed as adaptability to situations and conditions. However, as with the literature review, estimates and claims can be questionable due to the lack of reliable data that validate them, especially with the considerable time pressure at a demolition site and the omission of references to adequate building documentation.

4. The state of the art: conclusions and directions

4.1. Estimation

An acknowledged problem in literature is that gross estimates involving abstract proxies like ‘dwelling’, ‘building’ or even ‘single-family semidetached house’ cannot be easily validated due to regional, typologic and other variations (Ortlepp et al., 2015). Buildings in Switzerland and Sweden may be similar but those in Cape Town have flat roofs and no heating, resulting into different metal content (Wittmer and Lichtensteiger, 2007). Equally important to environmental and typologic factors are the dynamics of buildings, which make estimations rather hard, e.g. unreported or poorly documented changes such as details modified by contractors during construction (Mulder et al., 2007) or renovations that result into hibernating metal stock like old piping (Kleemann et al., 2016)

Concerning C&DW, we often lack actual data and opportunities for verification (Wu et al., 2014). While we know that metals are present, confidence in estimations tends to be weak, so wide ranges are applied to compensate for the low reliability (Mália et al., 2013). Furthermore, there is variation due to the type of C&D activity: new construction projects may be precisely reported, while renovation and demolition are generally insufficiently documented (Bergsdal et al., 2007). In the end, what remains is a vague picture of potential rather than information that can support policy, planning, design or management. It is therefore questionable whether it makes sense to continue with such indicative estimations.

From a methodological viewpoint, the units applied to C&DW measurement are also a matter for concern (Martínez Lage et al., 2010), with measurements ranging from t/m^2 to kg/c (Mercader-Moyano and Ramírez-de-Arellano-Agudo, 2013; Wittmer et al., 2007). For waste, mass (kg) seems a safe choice, certainly for metal to be recycled. For the sources of the waste, leaving puzzling estimations like per capita aside, there is too much emphasis on the gross floor area of buildings (m^2), which seems a poor proxy, as it bears an uncertain relation to the 3D walls, floors, roofs etc. that contain the materials that interest UM. Even the number and size of central heating radiators (the major source of iron in a building) is related to the volume rather than the floor area of the spaces they heat. It seems that estimation methods are based on the easy availability rather than the *relevance* of data.

4.2. Refinements and improvements

Literature abounds with attempts to improve the reliability and specificity of C&DW estimations through rules (Stephan and Athanassiadis, 2017), likelihoods (Schebek et al., 2017), preciser indicators (Ortlepp et al., 2016) or product groupings (Wittmer et al., 2007). The results tend to be incremental improvements and refinements, still bounded by the high abstraction of the proxies. Some of the most interesting attempts concern the use of cadastral data and GIS to provide overviews at city or regional level (Cheng et al., 2018; Kleemann et al., 2017; Oezdemir et al., 2017; Xue et al., 2017). These overviews utilize the potential of cadastres as sources of information on buildings and are provide broad estimates of UM opportunities that could support abstract decision making, e.g. policies or business models. They may even allow for localization at city level, e.g. which buildings may contain specific resources. Unfortunately, the underlying data remain vague and unconnected to the particular details and histories of the buildings from which they derive. This renders the overviews rather vague and uncertain, even concerning the feasibility of policies and business models, as there can provide no indications of how much might become available, in what condition and when, i.e. the service life of specific materials.

Other researchers have sought additional information from other sources, which have become widely accessible only recently, e.g. aerial or street photographs (Kleemann et al., 2016; Oezdemir et al., 2017). These sources complement cadastral data with e.g. indications of cladding materials and roof types, as well as of changes in the volume or appearance of a building like a loft conversion. Unfortunately they provide no indications of other, more frequent changes inside buildings, like kitchen or bathroom renovations, which may involve materials with high annual replacement rates (Stephan and Athanassiadis, 2018).

Considering how such attempts try to compound data from various sources to improve specificity, it is rather puzzling that UM studies make little use of primary building information sources like drawings and bills of materials, even though such sources may be available and accessible: 29.30% of the whole housing stock in the Netherlands is owned by housing corporations (CBS, 2017), which have to have detailed and accurate documents on their properties and their histories. If one adds to these listed and recent buildings, which tend to be well documented, it is probable that for half of more of the residential stock in Amsterdam can be explored and analysed in considerable detail. Such detail supports estimates of quantities and connects these estimates to building components so as to account for variability in composition and lifespan, as well as for relations to their context (e.g. adjacency to pollutants). When detailed information is used, e.g. bills of materials in combination with construction types, it becomes possible to be quite specific about which materials may be outgoing from certain buildings and in what quantities (Stephan and Athanassiadis, 2018). This is a far cry from grand, indiscriminate totals of urban ores for whole areas (Cheng et al., 2018). From a circularity viewpoint, knowing the precise context of a building component and through that how it is assembled and exposed to wear is significant for determining not only ease of extraction but also whether it can be re-used, repurposed, remanufactured or recycled.

The technical problems concerning retrieval of relevant information from various AECO documents are not insignificant but comparable to e.g. material estimation from street or aerial photographs. Moreover, they can be alleviated through Building Information Modelling (BIM), the currently preferred choice for information integration in AECO (Eastman et al., 2011). BIM promises a unified model as basis for all actors, actions and transactions in a design or construction process, and a dynamic environment for information processing throughout the lifecycle of a building, with significant benefits to owners and operators, and hence utility in the operation stage (Bosch et al., 2015). In UM research BIM has been identified as an appropriate framework for information management: some studies have extended BIM with waste management for improving building design and making waste predictions or have used it as basis for precise calculations of resources (Akanbi et al., 2018; Akinade et al., 2016; Cheng and Ma, 2013). Such calculations use intermediate proxies (mostly building elements like reinforced concrete columns and beams), which are more effective as basis for decisions and policies (Gerst and Graedel, 2008). Additionally, BIM supports the integration of RFID and sensor data that facilitate e.g. better estimation of stress properties over the working life, disassembly, take-back and re-use of structural steel components (Ness et al., 2015).

In conclusion, BIM can integrate all information from relevant documents, including construction documentation and on-site investigations for material extraction, as well as documentation from AECO processes that occur in the lifecycle of a building (e.g. building permit for a loft conversion). The end result is a comprehensive, coherent and consistent information system that utilizes the potential of computerization for UM (Wu et al., 2014), not only for making precise estimations but also for clarifying relations between components containing valuable resources and various contextual factors (including weathering and interfacing with other components), which often form key determinants of technical feasibility or economic viability in recovery.

4.3. Validation, verification and localization

The transition from abstract proxies to detailed information creates possibilities for validation and verification. These concern projections of material quantities, composition and flows, as well as the performance of C&DW processing. Knowing exactly what is present in a building makes clear its UM potential, including through comparisons with what is actually recovered from it at any time in its history.

Precise and accurate estimates of resources in buildings also include localization: identification of the exact building elements and components that contain these resources. Localization paves the way to integrating UM in regular AECO processes, not just demolition. Maintenance, minor improvements and major renovations during the use stage of a building's lifecycle may release end-of-life building components either usable in a different setting or containing usable resources, moreover with some regularity and in volumes that deserve attention.

4.4. Renovation and refurbishment

Connectivity to AECO processes is important for sustaining and possibly amplifying UM in buildings. Current interest in metal recovery is clearly linked to demand and the high prices it causes. However, even after a demand peak, the accumulated amounts of urban secondary resources remain a major environmental and economic issue (Huang et al., 2013). The reduction of new construction activity in combination with the preservation tendency in architecture (Huuhka and Lahdensivu, 2016) is making renovation increasingly important in AECO. In many cases, renovation is already outweighing in value new construction work (Cheng and Ma, 2013), even for residential buildings (Wang et al., 2015), where some renovation types have a WGR nearing that of the demolition (Cochran et al., 2007). Consequently, one would be wrong to consider buildings as static, invariable stock resources (Cossu and Williams, 2015); in fact, many materials may be considered as flow resources that exit the built environment with regularity and variability (Stephan and Athanassiadis, 2018). Connecting UM to the AECO processes that release them therefore becomes quite important.

4.5. Scope for urban mining

There is also a question of *scope* for UM: if both literature and the local analysis agree that metal recovery from C&DW is as high as it can get, what can UM in Amsterdam add in terms of efficiency or performance? Is there room for UM next to what already happens in the C&DW processing chain? History can be helpful in this respect, as enthusiasm for UM is not new; it is a recurring theme in times of extreme need like war. Analyses of wartime UM suggest that there are inherent limitations that cannot be ignored: during the first world war in Austria, up to 80% of copper for the munitions industry came from secondary sources but perhaps as little as 10% of the total amount of copper in use was amenable to extraction due to reasons like high cost or significance for other critical uses (Klinglmair and Fellner, 2010). Moreover, the initial drive and performance appear to have waned after the first year, presumably because the low-hanging fruit had been already picked. One could therefore put forward that UM may become a similarly short-lived bandwagon unless structurally embedded in AECO processes, where its economic contribution, however small, cannot be negligible. Otherwise, one should relegate buildings to long-term urban mines, in contrast to short-term ones like WEEE (Arora et al., 2017), confine UM to hibernating stocks, which for some reason are not part of traditional C&DW handling processes (Krook and Baas, 2013), or even prolong the life span of buildings as an alternative to UM towards improving sustainability and reducing waste (Cheng et al., 2018).

5. Discussion

The purpose of this study was to understand the state of the art in UM and compare it to local practices and conditions. Literature offers little certainty concerning the promise of UM for metals in residential buildings in Amsterdam. Existing studies employ high-level proxies to produce considerable variation in estimates that seem less reliable, complete or accurate than required for validation and verification, let alone for developing long-term policies, regulations or business plans. More certainty is necessary for overcoming lock-ins of current institutions structuring decision-making (Eames et al., 2013; Loorbach, 2010).

Existing C&DW processing arguably manages to recover resources to a degree that seems hard to improve. Metals, in particular, appear to be in an almost closed loop that allows for indefinite recycling without loss of performance. However, this relates primarily to demolition, which is both better regulated and organized than other AECO activities. It is moreover hard to verify because of the rather vague and incomplete estimates of resources in buildings.

What is arguably lacking in both issues is connections to AECO. AECO documentation provides detailed, precise and accurate data for estimating quantities, qualities and locations of resources in a building in a reliable and transparent manner. This is essential for evaluating both the UM potential of buildings and the performance of current C&DW practices. Probably even more significant are connections to AECO processes. The main reason for those is that through these one can determine realistically when and how components rather than materials they could be extracted from the built environment. This establishes true opportunities for recovery, even in residential buildings with their often small but repetitive alterations. If renovation and refurbishment of buildings regularly produces significant amounts of C&DW, as suggested in literature, residential buildings can become significant secondary sources of various materials (not necessarily metals) throughout their use without any negative consequences for their occupants. Connections to AECO also establish a framework for achieving higher forms of circularity, i.e. whether a component can be re-used directly or through repurposing or remanufacturing rather than merely recycled to recover its materials.

AECO professionals who design, plan and execute related activities, as well as building owners, should become aware of the value of what is removed during these activities and how it can be further processed in efficient material cycles. Analyses of such processes on the basis of adequate and reliable information could determine whether UM is already covered by existing C&DW processing, whether there is room for improvement in current AECO practices (which seems generally probable, given the fragmented institutional character of AECO and its operation in multiple markets and in distributed project teams (Van Bueren and De Jong, 2007)) or for additional UM activities outside AECO, and which policies, regulations, financial and societal motivations can combine to help achieve the wider goals of circularity in cities (Eames et al., 2013).

From a computational viewpoint, the use of GIS for comprehensive and coherent overview is a positive step for presentations of general UM potential. However, critical analyses of this potential should not be restricted to overviews or to available open data (e.g. cadastral ones); they should extend to specific characteristics of particular targets such as metals, residential buildings and the places like Amsterdam with their own legal, architectural and practical constraints. It follows that UM studies as well as AECO should invest more in BIM and the opportunities it presents for identifying end-of-life building elements and components in the lifecycle of the built environment.

Finally, focusing on specific resources like metals allows for in-depth investigations of possibilities and limitations, including clearer connections to the context of these resources (especially the lifespan of components that contain them and relevant AECO processes), as well as specificity in the information required for identifying and quantifying them. Generalizing by aggregating the potential of specific materials offers higher certainty than abstract, proxy-based, cumulative estimates of total mass in buildings, cities or regions.

Acknowledgements

The research was supported by a Stimulus grant from Amsterdam Institute for Advanced Metropolitan Solutions (AMS).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.06.024.

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