PUMA – from building to urban mine

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Importance for Amsterdam

Prospecting for metals in residential buildings of Amsterdam is an interesting exploration for reasons that stress the importance of recovering resources from the anthroposphere. First, there are indications that the larger the size of a community, the higher the building and demolition activity [1]. Second, higher waste generation rates (WGR) have been observed for construction and demolition waste (C&DW) in countries with higher population densities [2]. The underlying reasons for both include higher economic activity, population mobility, higher living standards and stricter environmental regulations: all characteristic of old yet still dynamic urban centres like Amsterdam.

The focus on metals and residential buildings makes it moreover possible to test hypotheses and methods of urban mining with specificity, going beyond hypes and towards thorough feasibility analyses of true possibilities for a new activity in the built environment.

C&DW

Construction and demolition (C&D) are widely acknowledged as one of the most important sources of waste, so there is little need to dwell on its position relative to others. It probably suffices to mention that 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 [3].

C&D is generally divided into new construction, renovation and demolition. Demolition contributes up to 70% of C&DW in some contexts [4]. In others it is calculated at 55%, with renovation producing 29% and new construction 16%, while demolition is 8% of the total building and construction activity, renovation 40% and new construction 52% [5]. Waste generation per gross floor area (WGA) at demolition is reported as being twenty times more [5] or even fifty times more than new construction [4]. Renovation WGA is estimated at five times more than new construction [5]. The above data make demolition a clear priority concerning C&DW but also stress the importance of renovation through the combination of high activity and relatively high WGR.

Metals from anthropocentric stock

Given the high prices for metals in the recent past, interest in re-using and recycling metals from waste is hardly surprising. 30% of copper consumed in Europe and 50% of iron in the USA originates from secondary sources [6], while in Australia 65% of steel is recycled, including upscaling of old cast iron [7]. Ambitions for the future remain high: in China, copper, iron, aluminium and lead substitution rates in (replacement of primary metal sources by secondary ones) through urban mining can be up to 50% by 2030 [8, 9]. Recycling of metals is also significant within the waste industry itself, as it significantly reduces its net carbon footprint [10].

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 [11]. This makes C&D important in comparison to other waste sources. For copper recovery it is one of the most promising sources, together with electrical and electronic equipment (the clear leader) and end-of-life vehicles, especially in terms of mass flow, where it competes with industrial and municipal solid waste [2]. Metals in generally represent 3% of all C&DW according to most sources [2, 12], although some estimates go up to 13,5% [13] – 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 important here, too. In Norway it is estimated that renovation produces eight times more metal waste than new construction, while demolition goes up to eighty times more [5].

Residential buildings

In demolition, non-residential buildings dominate in terms of floor area in most European countries. Furthermore, the demolished non-residential buildings are much larger and newer than residential ones [1]. In terms of WGA, there are relatively small differences between residential and non-residential buildings, except for renovation, where non-residential building produce four times more C&DW [14].

Interviews with Dutch small and large demolition firms support this picture, also with respect to metals due to the higher concentration of wiring and piping in non-residential buildings like factories and offices. In residential buildings, the elements that contain metals can be divided into three key categories:

- The load-bearing structure, both main and sub-structures, consisting of walls, floors, columns, beams etc. Structural elements are mainly composed of metals, concrete or wood.
- Building services, such as heating elements, pipes (tap water, rain water discharge), wiring, elevators (in high-rise apartment buildings).
- Façade and roof cladding, were for example copper or zinc panels can be used to completely cover rooftops or facades, while lead is used for waterproofing (counter flashing)
- Windows and doors, where metals like iron (before WW II) and aluminium (post-WW II) were occasionally used.

Current performance

The combination of high metal prices, the theoretical 100% recyclability of metals, their potentially endless lifecycle and their high efficiency of separation from other waste, as well as measures like landfill bans for recyclable waste, expectations are high: 100% recycling of metals is a key goal in C&DW recycling [10]. Of metals embedded in concrete, 90% is expected to be recovered and recycled [9].

Such expectations are not out of tone with general recycling performance in C&D: annually 94% of C&DW in the Netherlands is successfully recycled [3] [3], albeit mostly in downgraded forms, e.g. as materials for road building [15]. By comparison, the target set by the European Commission in 2008 is 70% recycling of C&DW by 2020 [16]. 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 [13, 17].

Interviews with demolition and waste processing firms confirm this: metals are practically always recovered at some point in the processing chain and mostly recycled. In terms of recovery, there seems to be little improvement possible. Metals appear to be in a closed-loop system, as far as C&D processes are concerned. Economics, regulations as well as social involvement play a role in this system.

Metals are considered a valuable commodity, so they receive particular attention in e.g. demolition projects. Metals present in a building are identified by visual inspections beforehand, mostly based on experience rather than documentation. Demolition experts can be considered experts on value recognition. They are very well aware of the potential value of materials to be extracted in general and in many cases of the value of specific materials and components to particular potential buyers. Demolition firms are well connected and capable of recognizing or even anticipating market demand for materials from secondary sources.

Waste separation at the source is required by Dutch national building regulations [18]. The regulations mainly concern hazardous substances but firms in the C&DW sector appear willing to go beyond their legal obligations. In case of metals, there is a clear financial drive but corporate responsibility, including environmental awareness, is becoming a relevant factor as well. Some demolition firms initiate far-reaching agreements with manufacturers of construction products, e.g. on how to supply C&DW in a manner it permits direct re-use in a production process so as to reduce the need for raw materials from primary sources.

Overall, the C&DW industry appears aware of opportunities, skilled and knowledgeable. The structure and applications of the chain may seem variable and ad hoc but this means adaptability to situations and conditions so as to take into account financial, time and other constraints without loss of valuable resources: in in the end what can be re-used or recycled is extracted from C&DW, especially metals.

Estimation approaches

Key to all studies of urban mining are approaches to the estimating the quantities and composition of metals in use. In general, there are two fundamental approaches [19]:

1. *Top down:* estimations from the balance between the amount of metal entering use and the amount of metal exiting use in end-of-life products or other waste. This approach requires reliable data over several decades.
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 because of the availability of data on proxy indicators like buildings or motor vehicles [11]. The main problem lies in the reliability of estimating the metal composition of such indicators [20].

Estimating the metal content of a building can be done in a number of complementary manners, ranging from construction information in conjunction with site visits to lifetime analyses (top-down approach) to end-of-life investigations through inspections prior to demolition and generalization from precedents [21, 22]. Typically, combination of the above are applied to arrive at reliable results.

However, what holds for one building may not apply to another: with buildings it is more difficult to generalize than with e.g. motor vehicles because buildings are seldom mass produced in an industrialized manner [23]. Still, common characteristics and components lead to the recognition of fairly standardized types at some abstraction level. At such levels we are tempted to apply rules of thumb like the ones found in technical textbooks on construction to arrive at some basic estimates across a range of buildings.

It is therefore to be expected that 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 have bearing on the material composition of a building. As a result, literature contains a wide range of various estimates for the metal content of buildings:

- 14-75 kg/m^2 of steel in Chinese residential buildings, depending on the period and type of construction [24]
- 606 kg/c of iron in residential buildings in New Haven, CT; for copper in the same municipality we have a more analytical breakdown [19]:
    - 28 kg/c in plumbing (as opposed to 32 on average in the USA)
    - 25 kg/c in wiring (28 in the USA)
    - 3.1 kg/c in air conditioning and refrigeration (16 in the USA)
- 195 kg of copper per single family house in Australia or 110 kg per shared living complex and
- 290 kg of zinc per single family house in Australia or 188 kg per shared living complex [11]
- 80 kg/c of copper in Switzerland (40% in the roof and 30% in power systems), with a comparable 60 kg/c in Stockholm, while in Cape Town its 5-10% of European cities, out of which one third is in sanitation and two thirds in power systems [25]

Probably the best illustration of the fuzziness can be found in a comparison between estimations of a study on a number of German buildings with the results of precedent research [21]:

- 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 C&DW, similar variation can be observed:

- Metal waste in Florida [12]:
    - Residential construction or extension: 0,30 kg/m^2 (wood frame) or 1,5 (concrete)
    - Residential demolition: 10 kg/m^2 (wood frame) or 15 (concrete)
    - Residential alterations: 0,75 kg/m^2 – but roof replacement: 6,8
- Metal waste in residential renovation: 0,4-6,8 kg/m^2 [14]
- Steel C&DW [26]:
    - Construction waste in China: 4 kg/m^2 but 5,1 according to transportation records, while in other research it has been reported as 6 kg/m^2
    - In the USA: 0,9 kg/m^2
    - In Norway: 0,48 kg/m^2
    - In Korea 4,53 kg/m^2

Observations

An acknowledged problem in literature is that general estimates cannot be easily validated due to regional, typologic and other variations [20]. Buildings in Switzerland and Sweden may be similar but those in Cape Town have flat roofs and no heating, resulting into different metal content [25]. Equally important to environmental and typologic factors and features are the dynamics of buildings, which make estimations rather hard, e.g. through renovations that result into hibernating metal stock like old piping [21] or unreported or poorly documented changes like details modified by contractors during construction [15].

Concerning C&DW, we often lack actual data and opportunities for verification [22]. While we know that metals are present, confidence in estimations tend to be weak, so wide ranges are applied to compensate for the low reliability [14]. Furthermore, there is variation due to the type of C&D activity: new construction projects tend to be precisely reported, while renovation and demolition are generally insufficiently documented [5]. Interestingly, there is more literature on waste production in new construction than in demolition and even less on renovation.

In the end, all we have is estimates that are useful in the absence of precise and accurate data, primarily for high abstraction levels that paint a vague picture of potential rather than support for policy, planning, design or management. It is therefore questionable whether it makes sense to continue with the refinement of such indicative estimations.

From a methodological viewpoint, the units applied to C&DW measurement are a matter for concern [27]. For waste, mass (kg) seems a safe choice, especially for metal to be recycled. For the sources, leaving grand totals and estimations 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 'solids' of architecture: the walls, floors, roofs etc. that contain the metals that interest this study. It seems that estimation methods are based on the availability rather than the *relevance* of data.

More significantly, there is a question of *scope* for urban mining: if both literature and the interviews agree that metal recovery from C&DW is as high as it can be, what can prospecting for metals in Amsterdam add in terms of efficiency or performance? Is there room for urban mining for metals next to what already happens in the demolition and waste processing chain?

Enthusiasm for urban mining is not new; it is a recurring theme in times of extreme need like war. Analyses of wartime urban mining suggest that there are inherent limitations that cannot be ignored. For example, in Austria during the first world war, 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 [6]. Moreover, the initial drive and performance appear to have waned after the first year, perhaps because the low-hanging fruit had been already picked.

PUMA products and audiences

Abstract projections make urban mining quite attractive initially but closer inspection of existing practices and possibilities suggests that opportunities may be fewer than assumed. One such opportunity is to establish precise and comprehensive processes of data collection, estimation, validation and verification. These can be beneficial to C&DW management, especially at the policy level, provided they go beyond static estimations and take into account the lifecycle dynamics of building to provide a permanently up-to-date picture of true possibilities. To achieve this goal in an efficient and effective manner, one needs to utilize existing information sources and integrate them in a comprehensive hierarchical representation that covers all necessary abstraction levels.

BIM has already been identified as an appropriate framework for building information management concerning urban mining. Existing attempts have extended BIM with waste management facilities that can be used to improve building design and make waste predictions [17, 28], as well as through the addition of RFID and stress sensor data that facilitate better estimation of stress properties over the working life, disassembly, take-back and re-use of structural steel components [7].

BIM can integrate all information from relevant documents, including the construction documentation and on-site investigations that are essential for metal extraction [21], 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 model that makes extensive use of the potential of computerization for waste management [22] and serves a variety of purposes for owners, occupants, authorities and AECO professionals, allowing them to access the information they need. The model helps them move from generic commodities like buildings to intermediate quantities like wiring and piping (including hibernating stock) or at least building elements or components like reinforced concrete columns and beams, which are more effective as basis for decisions and policies [23].

The structure of BIM also allows us to tackle problems of uncertainty and incompleteness: if information on parts or aspects of a building is missing, it is possible to use proxies like generic default properties for the particular part or aspect, or preferably data from precedents: documented buildings of the same period or type. The organized housing development of the Netherlands holds significant advantages with respect to such reasoning.

Reversely, abstracting detailed information into more compact estimates becomes significantly easier, transparent and reliable, as well as relevant: metal content can be described in a manner appropriate to the C&D activity, e.g. volume of reinforced concrete elements, area of a roof, wall length in a dwelling. Finding the appropriate unit (building dwelling, kg/m^2, kg/m^3) for an activity (renovation of a bathroom or kitchen, rewiring or replacing the central heating system) becomes an exploration of easy-to-generate alternatives from the same model.

Such variable abstraction and connectivity to AECO processes is also important for sustaining and possibly amplifying urban mining within rather than next to existing AECO practices. Current interest in metals is unambiguously 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 [24]. The reduction of new construction activity in combination with the preservation tendency in architecture [1] is making demolition and renovation increasingly important in AECO. In many cases, renovation is already outweighing in value new construction work [17], even for residential buildings [9], where some renovation types have WGR nearing that of the demolition [12].

By its partial nature, renovation is related to selective demolition (a.k.a. deconstruction), a promising practice for both environmental and economic reasons: conventional demolition is more sensitive to the final disposal costs of the waste operator than selective demolition, which carries higher labour costs (six times as much). Still, selective demolition costs are more balanced and hence less sensitive to any particular factor. Consequently, any efficiency improvement to selective demolition makes it even more attractive. From a technical perspective, selective demolition is in principle easier with modular, industrialized elements like prefabricated components, which tend to be easier to recognize and dismantle [15]. This makes it particularly relevant to practically all metal components in a building (plumbing, wiring, roofing) except for steel in reinforced concrete [29]. Supporting selective demolition in renovation requires higher precision and localization, not only for extraction but also for process needs, e.g. site management. BIM is capable of both providing the necessary information and processing it [17]. Processing can also cover additions like RFID tagging, which enables components to be identified, tracked and located in existing models, and imported into models of new buildings [7].

Conclusion

In the framework of PUMA we can develop a comprehensive, reliable approach that makes metal extraction and C&DW management in general more transparent and reliable. To achieve this we abandon questionable, poorly verifiable and unvalidated estimations, and prepare the way towards a BIM-based solution by:

- Comparing literature data to experiential data from interviewed specialists, so as to improve reliability and include difficulties in extraction
- Establishing a structure of relevant abstraction levels for estimation, starting with an *ordinal scale* (classification rather than a numerical value) at the top and ending with detailed BIM data at the bottom. These levels also involve various units, depending on the activity and its objectives. For the highest abstraction level the *dwelling* is used as unit: an average two or three-bedroom apartment, maisonette or row house, with a kitchen and bathroom (areas of higher metal concentration). If differences between this prototype and the residential stock under investigation turn out to be significant, variations in the classification can be applied (e.g. subcategories). Such distinctions or exceptions can be supported by detailed BIM data.
- Correlating estimations with relevant building *features* and through these to AECO processes. For example, the type of roof, of the load-bearing structure and of the heating system largely determine the metal content of a building. The *localization* of metals through such features can also be translated into opportunities for urban mining in conjunction with specific activities, e.g. the renovation of a roof or a loft conversion.
- Identifying possible *threats* to metal extraction, such as the presence of asbestos in a building. Contamination by asbestos makes processing of metals in C&DW a lengthy and expensive process that may remain technically feasibly but financially often makes little sense.

Towards a prospecting map

Available data sets and proxies

In order to create a map of the city of Amsterdam that reflects the potential of the city as an urban mine for metals, information on metal quantities in general needs to be combined with information on residential buildings in this specific city. First of all, residential buildings need to be singled out from non-residential buildings. The next step would be to use reliable documentation of the buildings in order to calculate and localize the metal content with precision. As stated above, BIM is preferable as documentation source but conventional drawings would suffice in most cases, offering the same basic information although little support for completeness, consistency and coherence.

Even if the documentation is rather abstract, e.g. in the form of sketchy drawings, it makes possible the use of intermediate proxies, in particular building elements of a known or presumed function and hence construction. In the absence of specific building documentation, one could use information derived from this documentation: housing typologies, general measurements like building height, or general features like the types of structure and building services. These provide general proxies that can be fuzzy and unreliable but nevertheless give a tentative indication of the metal content of a building.

These proxies can be derived several publicly accessible sources that contain such derived information:

- the Netherlands' Cadastre, Land Registry and Mapping Agency registers all buildings in the Netherlands; a public version of cadastral data is the BAG (Basisregistraties Adressen en Gebouwen, https://bagviewer.kadaster.nl);
- the digital Elevation Map of the Netherlands (Actueel Hoogtebestand Nederland, AHN) containing detailed information on building heights (http://ahn.arcgisonline.nl/ahnviewer/);
- the website maps.amsterdam.nl with interactive maps and open geo-data.

These sources contain valuable but limited information. Table 1 lists the relevant information and where this information is to be found.

Table 1

Type of information	**Source**
Building function: residential	BAG
Address	BAG
Floor area per housing unit [m^2] (verblijfsobject)	BAG
Building height (pand)	AHN
Number of housing units per building	BAG
Year of construction	BAG
Housing typology (incomplete)	Maps.amsterdam
Architectural value of building ("orde")	Maps.amsterdam

Information on the load-bearing structure, types and quantities of building services, façade and roof cladding or window and door frames is not available in full-scale data sets. Information on housing typology is not available for all residential buildings in Amsterdam.

Calculation of estimates

Using the above proxies, estimates for metal content have been calculated for an average Amsterdam self-contained dwelling unit of 55-75 m^2. The unit size is derived from national statistical data [30]. Each unit is assumed to have one kitchen, one bathroom and one separate toilet.

For each metal, each unit is assigned by default a number of points that reflects expectations from a typical dwelling:

- Copper: 2 (basic wiring, water pipes, taps)
- Steel: 2 (rebars in floors and/or walls, interior door frames, heating elements)
- Aluminium: 1
- Zinc: 1

When the unit is part of an apartment building or in a high or medium-rise flat, the quantity of rebars in the load bearing structure increases. Additionally, flats will almost certainly be equipped with elevators, although this concerns the building as a whole and is difficult to distribute per unit.

- If the building height is 7-17.5 m (2-5 floors, excluding attics), 2 points are added to the steel content
- If the building height is over 17.5 m, 5 points are added to the steel content

Quantities of metals due to wiring and piping do not vary greatly between average homes. However, units that are bigger than the average unit have more rooms and therefore more wiring and more heating elements. Houses over 150 m^2 are likely to have a second bathroom and/or an extra separate toilet. This influences copper and iron/steel quantities. For the latter material, this is only true when the heating system exists of radiators and not e.g. floor heating, which tends to be the case in recently built or refurbished dwellings of the higher quality levels.

- If the unit floor area is 75-150 m^2, 2 points are added to the copper content and 2 to the steel content
- If the unit floor area is higher than 150 m^2, 4 points are added to the copper content and 4 to the steel content

Unfortunately, no data is available concerning façade or roof cladding. As a result, no estimates can be made concerning aluminium, zinc and lead in these parts of a building.

In terms of totals, the following classification is proposed:

- Copper
  - Class A: 6 points
  - Class B: 4points
  - Class C: 2 points
- Steel
  - Class A: 9 points of higher
  - Class B: 6-8 points
  - Class C: 2 points
- Aluminium
  - Class C: 1 point
- Zinc

- Class C: 1 point

These classes are difficult to express in terms of precise quantities not only for reasons of uncertainty but also due to the aforementioned lack of validated estimates on the basis of proxies. A tentative interpretation involves ranges (as fuzzy numbers):

- Copper
  - Class A: 35-80 kg
  - Class B: 15-55 kg
  - Class C: 5-35 kg
- Steel
  - Class A: 800-1200 kg
  - Class B: 600-1000 kg
  - Class C: 500-900 kg
- Aluminium
  - Class C: 4-9 kg
- Zinc
  - Class C: 5-8 kg

Another aspect that can be included in the classification is the risk of contamination from asbestos and extraction limitations (refurbishment and demolition restrictions due to monumental status. Alternatively, these could be added as separate classifications and corresponding indications on a map.

- If the construction year is 1950-1980, then the probability of asbestos contamination is high

- If the architectural value is “orde 1”, then the building has monumental status
- If the architectural value is “orde 2”, then the building is highly valued
- If the architectural value is “orde 3”, then the building is of mid value

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