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A comparative analysis of quantification and validation methods for prospecting the anthropogenic mine as material reserve for circular construction

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Abstract. Globally, buildings account for at least 39% of CO_2 emissions and more than 50% of resource extraction and solid waste production. Therefore, any transition to carbon neutral buildings must be paired with new resource sensibilities and a shift from linear models of material consumption to continuous material use within a circular economy. Prospecting the (urban) anthropogenic mine represents an essential step towards circular construction and requires a robust methodology for data collection and interpretation. This paper presents a comparative analysis of survey methods, evaluated by parameters of time, accuracy, equipment, and labor to determine the ability of each tool in providing the necessary data to activate the existing built environment as a material resource. Chosen methods span from on-site manual and analog surveys to off-site digital technologies on a variety of case study scales. In all cases, the output's data format (sketch book, images, mesh or point cloud outputs) can be cumbersome to process with CAD and BIM software, increasing time to results and limiting the technology's potential, introducing the call for a new generation of survey tools specifically addressing the needs of deconstruction and salvage in circular construction.

1. Introduction

Buildings account for at least 39% of global carbon dioxide emissions [1] and more than 50% of resource extraction and solid waste production. [2] Therefore, any transition to carbon neutral buildings must begin with new resource sensibilities and a departure from linear models of material consumption. A circular economy addresses the negative social, economic and ecologic effects of the current and dominant take-make-throw model and has been defined as an economy "that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times." [3] The consequent closing of production and consumption loops offers the possibility to end the loss of valuable finite resources and reduce dependencies on global, volatile resource markets, support new business models and green job opportunities, prevent greenhouse gas emissions, and mitigate the effects of the climate emergency. [4]

As global and local actors seek to address climate concerns, the implicit value associated with embodied carbon, labor, knowledge, and water will impact material valuation going forward. Already today, the amount of many metals and minerals bound in the built environment has outgrown their respective naturally occurring reserves. [5] Over the next ten years – critical to the effort of restricting global warming to 1.5 degrees –, carbon emissions from material production, transport, and construction (embodied carbon) will be responsible for 70% of total new building-related greenhouse gas emissions. [1] Embedded within a circular economy, circular construction thus calls for the activation of the already existing built environment as an anthropogenic mine, a material reserve for the construction of future buildings. [6]

Unfortunately, the industry has largely failed to documenting material stocks and flows within the built environment. Consequently, similar to naturally occurring mines, also anthropogenic mines require careful prospecting in an effort to understand which materials will become available for reuse or recycling when, and in what qualities and quantities. Detailed documentation represents an essential step towards circular construction and requires a robust methodology for data collection and interpretation.

However, the current debate and best practice on single building surveys for demolition or deconstruction tends to be more anecdotal than quantitative, limiting the potential for informed decision making. This aspect is especially surprising, when considering the increasing interest in high-quality datasets and added regulatory requirements on building passports [7] or demolition and deconstruction audits. [8] In an effort to shift the conversations, this paper provides a comparative analysis of suitable survey methods for the anthropogenic mine. Following a literature review and methods description in section 2, section 3 provides an overview of results from several case study buildings. Section 4 finishes with a comparative evaluation by parameters of time, accuracy, equipment, and labor to determine the ability of each tool in providing data necessary to activate the existing built environment as a material resource for circular construction and offers an outlook towards ongoing next steps in the development of survey tools at the Circular Construction Lab of Cornell University.

2. Tools and survey methods

2.1. Building surveys and reports

Building surveys, formerly known as "structural surveys" [9], are conducted by skilled surveyors for various reasons and in varying degrees of detail. Most commonly they serve to create measured drawings of existing buildings and for building value assessment. Typically, building surveys start with research by the surveyor and then continue moving on site. If there are existing construction documents or schedules for the structure, these can be used as reference. After assessing the building context and the building's exterior the surveyor turns their attention to the interior portion of the building. Finally, the survey is evaluated and concludes in a report that responds to the specific question of the client. [10] With respect to circular construction, detailed building surveys provide a foundation for the assessment, deconstruction, treatment and reintegration of materials and components through reuse and recycling.

Standard equipment for building surveys include measuring tools, paper or tablet for notes and sketches, a ladder, Personal Protective Equipment (PPE), a device for photographs, binoculars, a compass, and an electric torch. Whenever the survey exceeds the measuring of dimensions and assesses materials and their quality or condition, additional equipment is needed such as hammer and bolster, screwdriver, bradawl and a first aid kit. [10] Next to these common construction survey methods, soft- and hardware developments resulted in digital sensing tools (e.g. P2P laser distance measurement, LiDAR or photogrammetry) to perform (non-destructive) architectural surveys, enabling the quantification of building material content and its quality. [11-13] Following this trend, a recent generation of mobile tools with these capabilities is now also accessible to every-day users without the need of specialized equipment. However, questions of applicability, accuracy and compatibility with existing workflows often remain unanswered.

2.2. Areal or regional surveys and reports

Data sources and methods of data collection in assessing building material content at a regional scale vary. Top-down methods conduct physical surveys of individual buildings, sampling homes within a certain time-period and use this information to estimate the urban-mining potential of entire cities. [14] However, more recent studies have taken advantage of geographical information system (GIS) data to provide a more accurate, bottom-up methodology of assessing building material content. By applying building archetypes to spatialized GIS data, average material stocks at the scale of the building can be determined. [15-18]

Apart from demolition or deconstruction surveys aiming to evaluate the contemporary state of a building and its materials after its use, site surveys are also commonly used to assess urban conditions after natural catastrophes. So-called “damage assessments” estimate the extent of damage and helps organizing rescue missions. An industry standard for this procedure is Rapid Visual Screening (RVS) – a tool that visually compares and interprets high-resolution satellite images before and after a catastrophe to quantify damage. [19] The process of RVS is very obtainable and can be learned quickly without specific prior knowledge. [20] Damage assessment looks at the urban scale, rather than the single-building scale and is very time sensitive. Therefore, this method serves for rough estimates only with results that can have big margins of error.

3. Case study survey results and comparison

3.1. Manual on-site survey

A manual, on-site survey of a 3-story 1906 timber residential building in Ithaca, NY was conducted room by room, utilizing a tape measure to determine the dimensions of each space by measuring the walls and diagonals where possible. Additionally, ceiling heights, and door and window widths and location were measured and documented via sketches in a notebook. Following this process, several walls and ceiling cavities were opened using a hammer and a handsaw to determine the material content and widths of these sections, which were noted. Stud, joist, and beam spacing was also recorded.

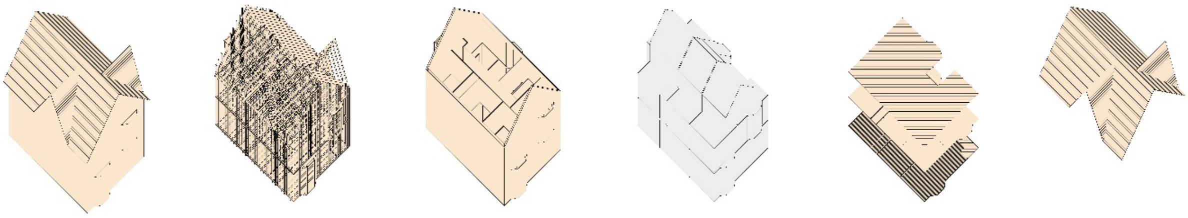

Figure 1. Digital model and material layers created by manual on-site survey.

Taking this information, a detailed 3D model was built using the CAD software Rhinoceros 3D. The information from opened cavities and documented spacing was assumed to be consistent throughout the entirety of inaccessible spaces in the building. The translation of the building into a 3D geometry simultaneously allowed for the calculation and evaluation of the building material content.

3.2. Digital off-site survey

For a pre-demolition material assessment of a church in Auburn, NY, a digital off-site survey has been implemented based on few personal interior pictures, and publicly available information via Google maps, street view, and image search. The interpretation and translation of such visual data into a 3D model was labor intensive and time consuming. This method depends highly on the availability of a range of pictures or the knowledge of the building elements through plans or a historical context, as undocumented or hidden elements might be missed, and material quantities underestimated.

Figure 2. Digital model and material layers created by digital off-site survey.

The resulting model served for a quantitative calculation of various building elements and building materials. The results are rough estimates with varying precision, based on the available digital data. The material conditions could partially be estimated through the available images.

3.3. Digital on-site survey

In a second step, a digital on-site survey was conducted at the case study building of section 3.1. Using an iPad equipped with the photogrammetry app Structure Sensor from Structure SDK, along with the Structure Sensor Attachment for iPad, 3D scans were taken on a room-by-room basis. With the sensor having a range of approximately 4 meters, rooms, stairwells, and hallways that exceeded that range were scanned in multiple parts, as necessary.

In using the scanner, the user should proceed slowly, holding the device approximately 2 meters from the surface being scanned, panning the device up and down as necessary to capture the ceiling and floor. When a corner is met, the user should take care to pivot slowly, then continue to follow the surface of the wall. Following the completion of the scan, an object file (.obj) and material texture file (.mat) are generated, providing mesh geometry of the environment and a 3D photogrammetry reconstruction.

Figure 3. (Unrolled) photogrammetry texture map created by digital on-site survey.

Following the scan, the mesh geometry contained within the .obj file along with the material texture can then be imported into Rhinoceros 3D for further processing. Unfortunately, mesh geometry is considerably difficult to work with in post-processing and requires very labor-intensive steps or newly developed algorithms for analysis. In a first step, through tracing the mesh, dimensions can be taken. The mesh can also be split and "unrolled" to communicate the scan via one elevation drawing, both in geometry and through the photo texture. While this method has obvious limitations with respect to geometric accuracy, the added information through the embedded image can offer very valuable insight in evaluation the quality of materials and its conditions.

4. Discussion and conclusion

4.1. Survey method comparison

The comparison of the survey methods in Table 1 clearly shows the benefits and limitations of each method. Manual on-site surveys show a high accuracy throughout with the downside of labor- and time-intense work. Digital off-site surveys on the other hand are time efficient but lack in accuracy, especially with increasing complexity and scale of spaces. They also depend on the availability of digital data from either online data sources or previous site visits. Often, publicly available data only exists for the exterior, and not for the interiors of a buildings, which makes this method very unreliable. Construction documents and bills of quantity from the time of the initial build or a renovation could fill this gap, but could not be located for any buildings in this study. Finally, the digital on-site survey provides high accuracy and minimal labor while the cost of technical equipment is high - if not rented. At a lower resolution, alternatives in the form of applications on cell phones or tables increasingly make these methods available to every-day users. For larger scales buildings (large ceiling height, far apart walls), these methods reach their technical limit, but new generations of hand-held devices not tested by the authors, such as the iPhone 12 Pro with LiDAR, have the potential to increase the accuracy of these scans. Regardless of these limitations, digital scanning technologies – while efficient on-site – still require intensive post-production due to their output formats, but provide valuable information in respect to material quality and overall building condition – as well as furnishing and appliances.

	Time	Accuracy	Equipment	Labor
Building Type I: Simple Space				
Manual On-site Survey	2	1	2	2
Digital Off-site Survey	1	2	1	1
Digital On-site Survey	1	1	4	2
Building Type II: Intermediate Space				
Manual On-site Survey	3	1	2	3
Digital Off-site Survey	2	3	1	2
Digital On-site Survey	2	2	4	2
Building Type III: Complex Space				
Manual On-site Survey	5	2	3	5
Digital Off-site Survey	3	5	1	3
Digital On-site Survey	N/A	N/A	N/A	N/A

Table 1. Comparison of different survey methods in the context of various building types. Scale from 1-5 (best to worst, matching grey scale) describes the relative factor of each individual parameter.

4.2. Conclusion and next steps

While advanced digital technologies can quickly provide a high degree of accuracy and an immense amount of data points, the same tools often are the most expensive, limiting widespread adoption. Newly developed tools utilizing smartphones or tablets on the other hand are widely available but reduce accuracy and compatibility. In both cases, the output's data format (point cloud and mesh outputs) can be cumbersome to process with CAD and BIM software, increasing time to results and limiting the technology's potential. At the same time, survey methods utilizing 2D data inputs and linear measurements may be preferable in contexts, where accuracy of dimensions is the highest priority. Further understanding that goals and available resources between e.g. a city planning authority and a proactive home-renovator are different, the selection of survey tools and methods is influenced not solely by merit but other parameters on a case-by-case basis.

With respect to building surveys aiming ease the reintegration of building materials and components from the anthropogenic mine into new construction, the study shows that there is not one preferable survey method. Rather, a combination of different tools is required at the moment to generate the necessary data points to create a detailed material catalogue of all elements in the building, evaluate these elements for their circularity potential and document connection details and deconstruction requirements. Lastly, there is currently no available tool to track building elements coming out of deconstruction in an effort to bridge the gap between demand and supply in circular construction. Consequently, next steps at the Circular Construction Lab at Cornell University include the development of (1) a new survey methodology that supports on-site measurements with augmented reality 3d scanning technologies [21], and (2) the Rhinoceros 3D plugin Rhino*Circular*, which allows the immediate calculation and evaluation of circularity potential of materials and connections in 3D geometries [22].

References

[1] Architecture 2030. 2020. "The Carbon Issue." *ARCHITECT*, January 2020.
[2] Transparency Market Research. 2020. "Construction Waste Market - Global Industry Analysis, Size, Share, Growth, Trends, and Forecast 2017 - 2025." Albany, NY.
[3] EMF. 2015. "Towards the Circular Economy: Business Rationale for an Accelerated Transition." 4. Rethink the Future. London: Ellen MacArthur Foundation.
[4] Hebel, D. E., M. H. Wisniewska, and F. Heisel. 2014. *Building from Waste: Recovered Materials in Architecture and Construction*. Basel: Birkhäuser.
[5] Nakamura, T., and K. Halada. 2015. "Potential of Urban Mine." In *Urban Mining Systems*, by T. Nakamura and K. Halada eds., 7–29. Tokyo: Springer.
[6] Heisel, F., and D. E. Hebel. 2021. *Urban Mining und Kreislaufgerechtes Bauen: Die Stadt als Rohstofflager*. Munich, Germany: Fraunhofer IRB Verlag.
[7] Heisel, F., and S. Rau-Oberhuber. 2020. "Calculation and Evaluation of Circularity Indicators for the Built Environment Using the Case Studies of UMAR and Madaster." *J. of Cl. Prod.* 243: 118482.
[8] European Commission. 2018. "Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings." Brussels: European Commission.
[9] Seeley, I. H. 1985. *Building Surveys, Reports and Dilapidations*. Houndsmills: MacMillian.
[10] Douglas, J., and E. A. Noy. 2011. *Building Surveys and Reports*. Chichester: Wiley-Backwell.
[11] Mosalam, K. M., S. M. Takhirov, and S. Park. 2014. "Applications of Laser Scanning to Structures in Laboratory Tests and Field Surveys." *Str. Contr. and H. Mon.* 21 (1): 115–34.
[12] Nex, F. C., and F. Rinaudo. 2009. "New Integration Approach of Photogrammetric and LiDAR Techniques for Architectural Surveys." *Proceedings of ISPRS, ed. by. F. Bretar, M. Pierrot-Deseilligny and M.G. Vosselman. Pp. 12-17*, 12–17.
[13] O'Donnell, J., L. Truong-Hong, N. Boyle, E. Corry, J. Cao, and D. F. Laefer. 2019. "LiDAR Point-Cloud Mapping of Building Façades for Building Energy Performance Simulation." *Automation in Construction* 107: 102905.
[14] Hu, D., F. You, Y. Zhao, Y. Yuan, T. Liu, A. Cao, Z. Wang, and J. Zhang. 2010. "Input, Stocks and Output Flows of Urban Residential Building System in Beijing City, China from 1949 to 2008." *Res., Cons. and Recyc.* 54(12): 1177–88.
[15] Lanau, M., and G. Liu. 2020. "Developing an Urban Resource Cadaster for Circular Economy: A Case of Odense, Denmark." *Envir. Sc. & Tech.* 54(7):4675–85.
[16] Mao, R., Y. Bao, Z. Huang, Q. Liu, and G. Liu. 2020. "High-Resolution Mapping of the Urban Built Environment Stocks in Beijing." *Envir. Sc. & Tech.*, April.
[17] Mastrucci, A., A. Marvuglia, E. Popovici, U. Leopold, and E. Benetto. 2016. "Geospatial Characterization of Building Material Stocks for the Lifecycle Assessment of End-of-Life Scenarios at the Urban Scale." *Res., Cons. and Recyc.* 123 (2017): 54–66.
[18] Stephan, A., and A. Athanassiadis. 2018. "Towards a More Circular Construction Sector: Estimating and Spatialising Current and Future Non-Structural Material Replacement Flows to Maintain Urban Building Stocks." *Resources, Conservation and Recycling* 129: 248.
[19] Anniballe, R., F. Noto, T. Scalia, C. Bignami, S. Stramondo, M. Chini, and N. Pierdicca. 2018. "Earthquake Damage Mapping: An Overall Assessment of Ground Surveys and VHR Image Change Detection after L'Aquila 2009 Earthquake." *Remote Sensing of Envir.*210 (June): 166–78.
[20] Das, P., S. Dutta, and P. Sengupta. 2020. "Damage Assessment of Recent Indian Earthquakes: Review of Existing Rapid Visual Screening Schemes." *Cur. Sc.* 119 (2).
[21] McGranahan, J., F. Heisel, and L. Lok. 2021. "AR De-Fab: Augmented Survey and Deconstruction Methodology to Maximize Material Circularity." Cornell University, NY.
[22] Heisel, F., and C. Nelson. 2020. "RhinoCircular: Development and Testing of a Circularity Indicator Tool for Application in Early Design Phases and Architectural Education." In *AIA/ACSA Intersections Research Conference: CARBON*. Pennsylvania.