ScanR: A composite building scanning and survey method for the evaluation of materials and reuse potentials prior to demolition and deconstruction

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Abstract. This paper introduces ScanR (Scan for Reuse), a composite method pairing quantitative and qualitative salvage and deconstruction surveying (S&D survey) with LiDAR and photogrammetry scanning in an effort to empower local municipalities and stakeholders in cataloging building materials prior to removal from site (in the case of either demolition or deconstruction), and enabling data collection and the generation of material databases to link local supply with demand – all in support of a shift from linear to circular economic models in construction. The speed of capturing large spaces through 3D scans and the ability to export such models into CAD software allows for a rapid assessment of surface and floor areas to calculate finishing material quantities and other material content, but lacks metadata such as quality and potential hazards that are necessary for a potential deconstruction contractor. Furthermore, information on spaces inaccessible to scanning, such as wall cavities, are necessary to comprehensively assess a building’s reuse potential. In supplementing scans with S&D surveys using accessible tools and software, these factors can be noted and referenced in relation to the space and 3d model, providing critical information to inform the harvest of materials and planning of the materials’ next use cycles. In testing this method on a building slated for deconstruction, this paper demonstrates the advantages of each method of data collection and how one can be leveraged to support the other to further catalyze local efforts to divert material from waste streams.

Keywords: building stock, survey, scanning, lidar, deconstruction, reuse

1. Background
Building materials and construction account for approximately 11% of annual global carbon emissions [1]. This, compounded by the expectation that global resource consumption will double by 2050 [2], makes it imperative that materials which are bound in the built environment today stay in circulation at their highest value and utility for as long as possible [3] in the effort to limit global warming to 1.5°C [4]. The most sustainable material is an already existing material; however, per the U.S. Environmental Protection Agency (EPA), 600 million tons (544 million metric tons) of construction and demolition debris (CDD) are annually generated in the US industry alone (of which the overwhelming majority is generated in demolition) and then downgraded or hauled to landfills [5]. In order to enable more...
sustainable alternatives to demolition on an industrial scale, several barriers to deconstruction need to be tackled quickly and efficiently, including but not limited to the current information gap with respect to available materials within a structure.

This paper introduces ScanR (Scan for Reuse), a composite method pairing quantitative and qualitative salvage and deconstruction surveying (S&D Survey) with LiDAR and photogrammetry scanning in an effort to empower local municipalities and stakeholders in cataloging building material prior to removal from site (in the case of either demolition or deconstruction), and enabling data collection and the generation of material databases to link local supply with demand - all in support of a shift from linear to circular economic models in construction. The speed of capturing large spaces through 3D scans and the ability to export such models into CAD software allows for a rapid assessment of surface and floor areas to calculate finishing material quantities and other material content, but lacks metadata such as quality and potential hazards that are necessary for a potential deconstruction contractor. Furthermore, information on spaces inaccessible to scanning, such as wall cavities, are necessary to comprehensively assess a building’s reuse potential. In supplementing scans with S&D surveys using accessible tools and software, these factors can be noted and referenced in relation to the space and 3D model, providing critical information to inform the harvest of materials and planning of the materials’ next use cycles. Through this heuristic approach - and their immediate linkage through software integration, the advantages of each method of data collection can be leveraged to support the other and further catalyze local efforts to divert material from waste streams.

2. Existing Tools for Material Inventories

A salvage survey represents an important first step in the deconstruction and salvage process as it provides both qualitative and quantitative data on the building as a material resource. The survey acts as a tool that can estimate both the quantity of material that can be reused, recycled, and disposed of, and its associated diversion rate. In the USA, four municipalities: Boulder, Colorado; Seattle, Washington; Palo Alto, California; and Cook County, Illinois have examples of salvage surveys that demonstrate the similarities and differences of this process.

The City of Boulder, Colorado offers a pdf entry fillable salvage survey that itemizes materials within a structure [6]. The tool solely tracks estimated recycling and reuse – not landfilled C&D debris, which the user must input from external sources in order to calculate diversion rates by pound. “User” in this case refers to the general contractor. In contrast, the City of Seattle utilizes a pdf entry fillable salvage survey which is to be completed either by the owner or owner’s representative, or a salvage verifier – depending on the size of the project [7]. The main body of the form is the “salvage assessment matrix” which itemizes materials in building components or bulk materials and their estimated quantity. Although Seattle has prepared this salvage assessment matrix, it also allows the use of alternate forms.

Palo Alto, California requires the use of a specific and verified reuse specialist “Reuse People” and their salvage assessment tool [8]. The Reuse People’s “Deconstruction & Salvage Survey” is a spreadsheet form that requires (next to general information) an itemized material list of building components by type, dimension, length, quantity, and additional description/species. In Cook County, Illinois, including Chicago and its surrounding region, general contractors are required to utilize Green Halo’s cloud system to generate the Demolition Debris Diversion Plan [9]. This system produces an itemized material list of estimated reuse and recycling and calculates the material diversion rate of a project. Table 1 below depicts variations within these 4 examples.
### Table 1. Comparison of four US municipalities’ salvage surveys (Boulder, Colorado; Seattle, Washington; Palo Alto, California; and Cook County, Illinois).

There are multiple intersections and diversions between the presented case studies. The struggle of municipalities that have implemented salvage assessments in the United States seems to be with the desire to allow for a system that is adaptable, but as a result, the data collection can become biased under the goals of the assessors, limited through the salvage form type, only provide a partial image of the building under questions of what is reported, and focus on diversion rates from landfills rather than the potential of salvaged material. This combination of choices limits the trustworthiness of collected data on a building’s salvage and adds an additional burden to all members of the process: owner, assessor, municipality, and planet.

At the same time, there are a variety of digital tools available today to assess building material stock at a range of scales. Light Detection and Ranging (LiDAR) technology has become more common in both bottom-up and top-down architectural surveys as a means of determining accurate building geometry. Aerial LiDAR information has proven to show strong results in informing the calculation of building stock models (BSM) and building energy models (BEM) of large urban areas [10, 11]. However, while the high resolution of these point clouds is enough to make strong estimates of material content on an urban scale, these scans lack detail at the scale of individual buildings. Because of the nature of these aerial scans, interior geometry can only be inferred from conditions observed on the exterior and consequently does not provide enough information for local municipalities, businesses and other stakeholders to accurately assess the material value of individual buildings. Handheld scanners available from manufacturers such as Leica Geosystems [12] show promise of bringing very high resolution to interior scans of buildings, but the price-points of these products create a barrier to entry for the average user, and data of such high resolution can be cumbersome to process without specialized computers and software. Therefore the authors identify new generations of LiDAR-equipped mobile devices such as Apple’s iPad Pro equipped with LiDAR scanning software as the ideal tool to pair with a deconstruction and salvage survey intended for the general public.

### 3. Methodology

In an effort to bridge the gap between a rigid and flexible survey, the authors recognize the potential of combining digital scanning methods with user-inputted data as a means to standardize data collection
while providing a broad range of options representative of the range of materials and conditions found in the built environment. The following section details the developed ScanR method for rapidly and accurately assessing the material content of a structure prior to demolition or deconstruction. **Section 3.1** introduces the case study for this methodology while the following **Section 3.2** outlines considerations taken in the development of the deconstruction survey; **Section 3.3** specifies how meshes are captured and **Section 3.4** describes the subsequent processing steps in Rhinoceros3D/Grasshopper. Following this, **Section 3.5** relays how quantitative data can be extracted from 3D mesh scans and finally imported into the tabular survey. *Figure 1* depicts a graphic representation of this workflow.

![Figure 1. ScanR Methodology Flowchart](image)

### 3.1 Application
A building representative of the general housing stock in Ithaca, NY was selected as a case study for the described method. *Figure 2* depicts a 4,500 ft², 3-story residential structure that was initially slated for demolition and has been deconstructed as part of the Catherine Commons Deconstruction Project [13]. Prior to any onsite work, the building has been surveyed using the ScanR survey method, both by the authors of this paper, as well as independently by architecture students of Cornell University after receiving a short workshop prior to visiting the site.

![Figure 2. 206 College Avenue pre- and post-deconstruction](image)

### 3.2 Salvage and Deconstruction (S&D) Survey
Taking from the evaluation of existing salvage surveys (*Table 1*), the developed S&D survey is a hybrid excel spreadsheet of quantitative and qualitative data, initial calculations, and summary metrics and graphs to provide users with an outline for potential material salvage and building deconstruction after as little as 30 minutes of being on-site. Performing a S&D survey requires a tape measure and minimal existing knowledge of buildings and construction. The survey is broken down into four parts which are to be performed on-site: “General Building Information,” “Preliminary Site Observations,” “Damage & Deterioration,” and “Material Inventory.” *Figure 3* illustrates the survey when the spreadsheet is initially...
opened. “Material Inventory” is the most robust section and includes subsections of raw building materials, building components, architectural elements, and other.

![Figure 3. Blank S&D Survey](image)

“General Building Information,” “Preliminary Site Observations,” and “Damage & Deterioration” use a series of fill in the blank, dropdown menus, and highlighting functions to provide initial qualitative feedback which provides background information and may be helpful to a salvage or deconstruction specialist in the planning stage of a project. “Material Inventory” constitutes the largest section of the survey and encompasses all the qualitative and quantitative measures which are to be gathered while on site. The focus of “Material Inventory” is to gather all the information which is not able to be comprehended by LiDAR or photogrammetry scanning. This includes material types, member dimensions in width, thickness, and length, quality, and methods of assembly. The matrix can be seen in Figure 4, which demonstrates the input of two types of siding into the survey. This process continues until the entire building is surveyed.

![Figure 4. Completed Siding Material Cataloged in S&D Survey](image)

This format allows the assessor to have complete control over the initial material inventory and supporting qualitative information but removes them from the calculations and metric production – reducing the error from miscalculations or variation from individual methods.
3.3 Scan Capturing
Scans are captured using LiDAR-equipped Apple iPad Pros running Polycam LiDAR scanning software [14]. To allow for an accurate account of geometries and materials within the spaces of assessment, it is recommended to ensure even and adequate lighting. Users should determine a path to travel through the structure, taking care to avoid scanning any given area more than once, as this can lead to duplicate data and misalignments in the final scan. While scanning, users should pan slowly around the spaces they are capturing and where possible stand at least 1.5 meters away from surfaces to be scanned. Once the survey is complete, the scan can be compiled locally on the iPad and exported as an object (.obj) file containing a mesh with an associated photogrammetry texture saved as a material (.mat) file, as shown in the scan of the case study building in Figure 5.

![Figure 5. Output of a PolyCam scan of 206 College Avenue visualized in Rhinoceros3D. Mesh (left) and Photogrammetry Texture (right).](image)

3.4 Mesh Processing
After the initial on-site scanning, off-site post-processing includes the import of generated meshes into Rhinoceros3D, a popular CAD modeling software in the architecture and construction industries. Using Grasshopper, each facet of the mesh is evaluated by the vector of its centroid’s surface normal. The surface normal is deconstructed into its X, Y, and Z vectors. Mesh facets with a Z vector greater than or equal to -0.95 units are categorized as ceiling surfaces, facets with a Z vector greater than -0.95 units but less than or equal to -0.5 units are classified as gable-roof surfaces, given their downward slope. Facets between -0.5 units and 0.5 units are classified as wall surfaces, those greater than or equal to 0.5 units and less than 0.95 units are considered stair surfaces and those greater than .95 units are binned as floor surfaces. These values are adjustable given the needs of each individual scan.
Following the automatic categorization of these meshes (shown in Figure 6), each facet’s area is taken and summed into the outlined categories (Floor, Wall, Ceiling, Roof, Stairs). This then allows the values to be exported from Grasshopper into a separate CSV file.

### 3.5 Linking Scan and Survey

A short python script links data exported from Grasshopper into the deconstruction survey, whereby each value is imported into its corresponding cell. The independence of these processes until this point allows either one to be performed first based on the assessor’s discretion; however, both processes are needed in order to receive results. These values are referenced in a number of calculations embedded into the spreadsheet which determine the building’s material contents. Referencing a library of archetype constructions [11], users can assign a matching assembly construction based on onsite observations and knowledge of the building’s construction date. Alternatively, they can also create their own material assembly. Those archetypes, which store information on material layer assembly and thickness, are multiplied by their corresponding construction’s surface area (e.g. the construction archetype’s data for walls is multiplied by the derived surface area for walls), resulting in a material assessment for the building by both volume and mass. Figure 7 demonstrates an S&D Survey with an assembly reconstruction using LiDAR scan surface area results.

These preliminary calculations assist in producing metrics that are usable for a wide range of options and users. Material Intensity (kg/m²) demonstrates the concentration of different materials throughout the building. This can provide contractors and researchers with the extent of a given material throughout a building or set of buildings. Embodied Carbon (kgCO₂eq) provides building owners, reuse specialists, and researchers with information on how materials contribute to the overall carbon footprint of the building. Considering the relative abstract nature of this value for those not well versed in the industry, two additional – more referential – comparisons are provided: the number of forest acres that are needed to sequester the given amount of CO₂, and the number of times an average car can drive around the
globe on the given amount of CO$_2$ tail-pipe emissions [14]. Additionally, total material tonnage is calculated to provide reuse specialists and contractors with insight into potential revenue streams, transport logistics, and eventual tipping fees for the project.

4. **ScanR Results**
   The results of the ScanR method for case study building 206 College Avenue are displayed in Table 2 and Figure 8 below.

| Surface Area (m$^2$) | Timber (kg) | Bio-Based Insulation (kg) | Plaster (kg) | Embodied Carbon Including Sequestered (kgCO2e) | Total Material Tonnage (US Ton) |
|----------------------|-------------|---------------------------|--------------|---------------------------------------------|---------------------------------|
| Exterior Wall        | 388.86      | 2286.53                   | 351.41       | 3704.74                                     | 4123.83                         | 6.99                             |
| Interior Wall        | 388.86      | 100.20                    | 0.00         | 7409.48                                     | 1132.94                         | 8.28                             |
| Floor                | 199.63      | 6441.68                   | 0.00         | 3802.94                                     | 9785.96                         | 16.70                            |
| Roof                 | 72.41       | 554.10                    | 475.32       | 4427.02                                     | 2246.70                         | 0.61                             |
| Stairs               | 47.36       | 491.10                    | 0.00         | 0.00                                         | 644.32                          | 0.54                             |
| Total                | 1329.58     | 9873.61                   | 826.74       | 19344.18                                    | 17933.75                        | 33.13                            |

Table 2. S&D survey results for 206 College Ave, NY

Figure 8. S&D survey results for 206 College Ave, NY

5. **Discussion and Conclusion**
   The success of the ScanR method is found in its ability to be implemented rapidly with minimal training via easily accessible tools. As found in the case study, where lightly trained students adopted the tool in an exercise, the average person was able to quickly understand the working of the method and perform a successful survey for the rapid assessment of a building. The average person working in the construction or salvage industry’s pre-existing familiarity with tabular data, and the ease with which one can capture a LiDAR scan with common devices indicates the potential scalability of this method. Additionally, the method’s reduced dependency on onsite measurements reduces overall survey time and potential for error by the assessor. This represents a great advantage in the use of the ScanR method and suggests that increased use of LiDAR scanning could work to improve the method further.

Present limitations of the methodology arise from the scanning capabilities of today’s mobile devices. As mentioned earlier, high-resolution products exist on the current market, but are not as accessible to users as mobile devices. It is the hope of the authors that coming generations of LiDAR-equipped devices will provide greater accuracy to the general public.
Limitations also arise from the reporting of initial material values within the S&D survey. The specification of building materials that constitute archetypes are based on the assessor’s assumptions. This carries the risk of errors or informed guesses in hard-to-reach places. To this extent, the assessor’s responsibility does not only include identifying the correct building components, but also encompasses the need to accurately flag toxicants, health and safety risks and other potential hazards, as well as quality assessments of the material content (e.g. water damage or mold). This opens the door to future research, as the advantage of LiDAR scanning lies not only in providing an accurate assessment of a building’s geometry but also in the embedded photogrammetry texture. The image analysis of this texture whereby image data analysis, machine learning (ML) and computer vision could be employed to assess material content, quality and dimensions while further reducing the need for specific user inputs (or, in the case of health and safety, supplementing and verifying user inputs).

Additional limitations derive from the availability and accuracy of data on material and construction archetypes. Due to limited data availability, the tool currently allows assessors to create unique archetype constructions, which also enables greater customization. However, a more robust construction archetype database will reduce errors from speculating on the dimensions and contents of specific assemblies between the visible layers of a scanned geometry and thus further increase the accuracy.

As this tool is used by stakeholders in the local construction and reuse industry, the collection and analysis of created datasets will be a valuable source of information on not only the collective material contents of all surveyed buildings but also on the flow of materials within the city (e.g. what is salvaged vs discarded). This data also helps build the existing library of construction archetypes based on user reports, thus improving assumptions about construction details in instances where opening wall cavities is not viable. This further work will become especially interesting once ScanR is more widely distributed and aggregated data begins to provide insights into the material content of the local built environment at large.

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