The Role of Augmented Reality and Governance in Improving Labour Productivity for Building Inventories: Insights from the Binckhorst Area

Juan Carlos Navares-Vázquez, Clara Garcia, Rizal Sebastian, Mario Villalba-Ferreira, Danielle Strydom, Simon Duindam, Mark Lommen, Ana Sánchez-Rodríguez, Pedro Arias, and Jesús Balado

Abstract As part of the SUM4Re project, which aims to create materials banks from the built environment through the circular economy, this paper explores the intersection of labour productivity, 3D data acquisition, and governance in the context of building inventories, with a particular focus on Binckhorst area (The Hague, The Netherlands). Although Augmented Reality (AR) devices were not designed to export 3D data capture, the integration of diverse sensors, such as LiDAR and RGB cameras, allow AR devices to become low-cost scanning tools as a viable alternative to more expensive conventional devices. In addition, governance aspects, and particularly the role of municipalities can facilitate data collection and sharing by regulating it. The Hague is a clear final example of Scan/BIM/GIS integration thanks to its 3D Mirror City. This study develops a theoretical-practical framework to assess labour productivity in building inventories, examining the cost implications of barriers and regulations that affect the efficiency of data collection processes. The framework is operationalized through a questionnaire designed to capture key elements of labour productivity. By integrating these three components, the study aims to contribute to the understanding of how innovative technologies and governance models can improve efficiency in the construction sector, foster circular economy practices, and promote more sustainable urban development.

J. C. Navares-Vázquez (✉) · C. Garcia · A. Sánchez-Rodríguez · P. Arias · J. Balado
CINTECX, GeoTECH, Universidade de Vigo, Vigo, Spain
e-mail: juancarlos.navares@uvigo.gal

C. Garcia
Human-Tech, Universitat Politécnica de Valéncia, Valencia, Spain

R. Sebastian · M. Villalba-Ferreira · D. Strydom
Research Group Future Urban Systems, The Hague University of Applied Sciences, The Hague, The Netherlands

S. Duindam · M. Lommen
Block Materials, Heerlen, The Netherlands

C. Cameselle et al. (eds.), *Sustainable Waste Management and Circular Economy*, Lecture Notes in Civil Engineering 803, https://doi.org/10.1007/978-3-032-15934-2_32

Keywords Urban mining · Construction and demolition waste · Mixed reality · HoloLens 2 · Building information modelling

1 Introduction

The construction industry plays a major role in the global economy but has a significant environmental impact. Since 2000, material consumption has tripled, with concrete, steel, and cement being the most resource-intensive [1]. Buildings account for 32% of global energy consumption and 19% of greenhouse gas (GHG) emissions [2]. Life Cycle Assessment (LCA) helps evaluate these impacts and improve energy efficiency. Accurate LCA studies require Life Cycle Inventory (LCI) and Material Flow Analysis (MFA) to assess material stocks [3]. The residential sector alone consumes 30–50% of global resources, creating significant environmental burdens but also opportunities for circular economy strategies [4]. However, a lack of comprehensive data limits effective decision-making.

The construction industry also faces challenges like low productivity and fragmented value chains, leading to inefficiencies and high construction and demolition waste (CDW) generation. Digitalization, such as through LiDAR data collection, improve 3D mapping enhancing productivity and accuracy. Integrating digital strategies and LCA can help address current constraints and improve sustainability in construction.

The objective of this work is to develop a theoretical and practical framework for evaluating labour productivity in building inventories, analysing the cost impact of barriers and regulations on data collection efficiency. This paper studies the application of various tools aiming to replace a fraction of manual labour by capital inputs.

2 Related Work

In recent years, 3D scanning in construction field has gained widespread attention due to increased automation. LiDAR, structured light, and photogrammetry help capture precise data [5]. However, traditional technologies are expensive and require specialized training to operate effectively [6]. One promising alternative is the usage of Augmented Reality Head Mounted Displays, such as Microsoft HoloLens 2. These allow to generate a 3D reconstruction of the environment in real time, allowing users to visualize and interact with digital models directly within their physical surroundings. These non-conventional tools can reduce the cost of the equipment up to 100 times. The possibility of real-time enrichment and interaction with the data also minimizes processing times and the associated costs.

Regarding applications of 3D building reconstructions, Liang [7] proposes a method that uses 3D laser to scan and restore a building. Antova [8] presents two applications based on portable LiDAR technology to reconstruct large buildings. Mariniuc et al. [9] work on obtaining correct measurement of buildings using different sensors like LiDAR or ZED stereo cameras. Other systems are focused on the virtualization and visualization of the reconstructed scenarios in Virtual Reality, such as Mora et al. [10].

Moreover, one prominent application is the integration of 3D scanning with Building Information Modelling (BIM) and Geographic Information Systems (GIS) [11]. This integration supports urban governance by facilitating data-driven decision-making and promoting the reuse of materials in line with circular economy principles.

3 Materials and Methods

3.1 The Binckhorst Area

The Hague has maintained a publicly accessible 3D Mirror City ("Spiegelstad") since 2017 as part of its smart urban management strategy. This digital twin of the city's physical environment, hosted on an ArcGIS platform, integrates diverse data sources, including traffic and public transport databases, monuments and city repositories.

The pilot site in the Binckhorst area of The Hague provides both a *Donor* and *Target* building as test cases for capturing circularity and material data, with a focus on building geometry and material characterization (Fig. 1). The city of The Hague owns a proportionately large amount of the land area in this neighbourhood, thereby increasing their influence and enabling circular strategies to gain a foothold in real estate developments. The integration of circularity data from these two buildings into the 3D Mirror City would be a significant step towards enriching the city's digital twin.

3.2 Governance

The literature review highlights significant barriers in governance models for sustainable urban construction logistics, such as lack of collaboration incentives, poor information-sharing, and misaligned stakeholder objectives [12]. These issues hinder the integration of AR technologies, which relies on strong coordination and data-sharing. To address this, the research explores governance models that support AR adoption and improve labour productivity in building inventories. Binckhorst presents an opportunity for governance innovation, enabling public-private collaboration to map buildings, sort materials and optimize reuse and recycling.

Fig. 1 3D Mirror city visualization of Binckhorst area: *Donor* (orange) and *Target* (blue)

To analyse Binckhorst's governance structures, the research team conducted desk research and interviews with key stakeholders, providing insights into challenges and opportunities for AR-based solutions.

3.3 3D Data Acquisition and BIM Generation

Non-conventional devices are becoming alternatives to professional scanners due to costs and sensorization improvements. HoloLens 2 stands out for its LiDAR and AR capabilities. Furthermore, its main limitations—drift over long scans, limited field of view, low point density and range compared to professional scanners—do not affect negatively BIM generation with the proper movements during the scan. The main geometry is recognizable, and magnitude orders are preserved in short scans.

A scanning methodology was developed using HoloLens 2 and the Reality Mesher app [13], allowing 3D data acquisition and virtual marker placement. The collected 3D point cloud data was used to create BIM geometry, starting with outer walls, floors, and ceilings, followed by interior walls, doors, windows, columns and stairs.

3.4 Labour Productivity

Labour productivity, defined as the ratio of output to labour input, measures how efficiently labour is used to generate output [14]. A Cobb–Douglas specification is used to capture both capital-labour substitution and diminishing marginal returns, which align with the empirical characteristics of the inventorying process:

$$P_{ij} = A_{ij} K_{ij}^{\alpha_{ij}} L_{ij}^{\beta_{ij}} \tag{1}$$

where P presents the output of the inventorying work, A represents the level of technology, K and L *are* the capital and labour inputs, with α and β representing output elasticities, respectively, capturing the responsiveness of output to changes in each factor input. Each type of information has different relations between factor inputs and outputs, with information required for legal and regulatory standards P_b being more capital-intensive as it requires more precise quantitative information (e.g. material strength, chemical composition) and information enhancing marketability by informing potential buyers P_y relying on more subjective assessments (aesthetic qualities, historical significance).

For circular construction, inventorying serves as an intermediate process that provides information ex ante, allowing for a more informed decision between demolition and deconstruction. The efficiency of inventorying has both a direct and indirect effect on the level of reusability of building materials. This relationship can be formalized through a profit function that captures the trade-off between inventorying costs and the economic returns from different deconstruction strategies:

$$\begin{aligned}\Pi = \sum_{i,j} \big[&\theta_{ij} \big(Y_{c,ij} - \big(O_{c,ij} + S_{c,ij} + B_{c,ij} \big) \big) \\ &+ \big(1 - \theta_{ij}\big) \big(Y_{d,ij} - \big(O_{d,ij} + S_{d,ij} + B_{d,ij} \big) \big) \big] - I \end{aligned} \tag{2}$$

where Π is the profit or loss of the deconstruction project and θ indicates the share of the materials that is deconstructed, since demo. Y, O, S and B stand for residual material value, organizational costs, demolition activities and legal costs, respectively, whereas c and d refer to circular deconstruction and traditional demolition respectively, and lastly I represents the inventorying costs. Through a questionnaire, the productivity-enhancing features of these instruments are assessed by examining the tools themselves, the types of labour and capital required for their operation, their applicability to different material and product types, and the limitations on their broader use.

4 Results and Discussion

4.1 Governance

The governance model in Binckhorst is fragmented, particularly in circular construction projects, where private sector innovations and public policies are misaligned, limiting the market potential of AR-driven material reuse. Key challenges include poor coordination, misaligned incentives, and insufficient data-sharing among stakeholders. To overcome these barriers, a multi-level, inter-municipal governance framework is essential to harmonize regulations, foster cooperation and support the adoption of low-cost AR technologies.

A harmonized regulatory framework across municipalities can ensure consistent AR-based inventory tracking and demountable building design standards, making material reuse more efficient and scalable. Cities should establish shared data protocols and align zoning laws and building codes to support AR-driven circular construction. Furthermore, municipalities can pool resources to fund regional AR pilot projects and provide joint financial incentives, such as subsidies for open-source AR tools and tax benefits for circular economy initiatives.

To strengthen market access for reusable materials, a regional AR-enabled marketplace should be developed, where stakeholders can exchange, track and certify materials using AI-powered verification. This would improve market transparency, trust, and accessibility, allowing both large firms and SMEs to participate in cost-effective AR-based material tracking.

Finally, an inter-municipal AR training hub should be established to equip construction workers with AR skills, ensuring that technology adoption translates into productivity gains. By embracing a collaborative, inter-municipal approach, cities can accelerate AR adoption, improve labour productivity, and drive a more sustainable and technology-driven construction ecosystem.

4.2 3D Data Acquisition and Integration.

The data obtained from HoloLens 2 was exported and visualized using CloudCompare (Fig. 2). The point clouds had an average of 250 points per square meter, with higher density on detailed areas. The registration was done manually against AHN4.

Despite the relatively low point density, all important structural elements were easily recognizable. This includes walls, floor, ceiling, columns and beams, but also windows, doors, stairs, etc. Furniture and other minor elements such as fire extinguishers are not considered in the context of this work. Subsequently, the BIM was loaded in ArcGIS Pro and georeferenced to OpenStreetMap (Fig. 3).

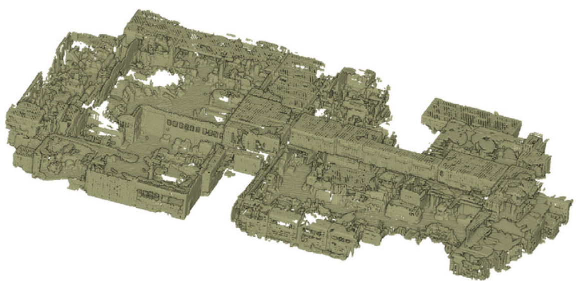

Fig. 2 Pont cloud of *Target* building scanned with hololens 2

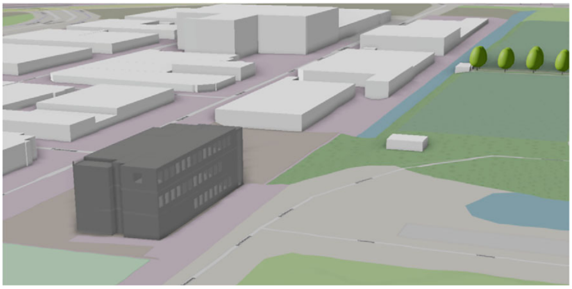

Fig. 3 ArcGIS visualization of *Donor* building BIM model (grey) on OSM with world elevation 3D

The enrichment of BIM models with circularity data, presents an opportunity to enhance city Digital Twins hosted on GIS platforms, such as The Hague's Mirror City, with information about circularity. These models are enriched with data connection to material databases, including CIRDAX (a platform dedicated to the inventorying of building materials and generation of material passports and building logbooks), CONCULAR (a smart tool enabling lifecycle assessment calculations based on material inventories, building resource passes and auditing) and GENIA (a webtool originally dedicated to the inspection and structural assessment of large infrastructure, which allows the incorporation and enrichment of IFC models).

4.3 Labour Productivity

The use of AR scanners in the inventorying process generates 3D point clouds, which can be digitally linked to various software tools, including those enhanced by AI. These tools allow for the addition of manual annotations to indicate the type and quality of materials, such as visible cracks or other damage. The primary advantage of these scanners lies in their ability to provide precise measurements of entire rooms or buildings, which is beneficial for creating a digital representation of the structure. However, while the accuracy of measurements is valuable, this information is only useful to link individual materials and products, which require further processing and interpretation.

The high costs of LiDAR technologies pose significant barriers to their widespread use in inventorying. The LiDAR scanner, priced around €30,000, provides high-quality results, but the expense may outweigh the benefits for certain applications. In comparison, the HoloLens 2, priced at €5000, offers lower-quality results but is considerably more affordable. While both tools enhance measurement accuracy, the time required for manually annotating the generated data significantly exceeds the time spent on scanning itself. This raises the question of whether investing in a 3D model as a blank canvas on which further information can be added is truly valuable for the goals of deconstruction and demolition, especially when considering the time and effort required for data interpretation. Using a table-like format like CIRDAX, in which material and product information can be stored, might prove equally effective with fewer capital input. Also, the 3D point cloud does not provide information on chemical composition of the materials.

Inventorying is crucial before deconstruction, guiding material reuse and tool selection. Without prior data, determining the right instruments is difficult, especially for material-specific equipment. For example, assessing a steel beam's integrity is challenging without prior access, adding logistical complexity and increasing costs. The high cost of specialized tools and training reduces their economic viability. LiDAR requires significant investment in equipment and expertise, which may not be justified given the limited role in deconstruction.

5 Conclusion

In this work, a 3D scanning of two buildings in Binckhorst area has been conducted with AR tools to ensure the circularity of the existing urban materials in a context where governance and labour productivity are essential. AR and LiDAR technologies enhance measurement accuracy but face challenges like high costs, manual data processing and limited applicability in deconstruction projects. In addition, governance inefficiencies hinder the adoption of AR and digital tools in inventorying and deconstruction processes. Collaborative governance models, standardized data-sharing and public-private partnerships can improve the efficiency of inventorying and material reuse strategies. To maximize sustainability and productivity, the industry must balance technological advancements with cost-effective solutions.

Acknowledgements We sincerely thank CHCNAV for providing the instruments and support for this research. This research has received funding from Government of Spain through RYC2022-038100-I by MCIN/AEI/10.13039/501100011033 and FSE+. This paper was carried out in the framework of the SUM4Re project (Creating materials banks from digital urban mining), which has received funding from the Horizon Europe research and innovation program under grant agreement no. 101129961. Funded by the European Union. Views and opinions expressed are those of the authors only and do not necessarily reflect those of the EU or HADEA.

References

1. Huang B, Gao X, Xu X, Song J, Geng Y, Sarkis J et al (2020) A life cycle thinking framework to mitigate the environmental impact of building materials. One Earth 3:564–573
2. Resch E, Lausselet C, Brattebø H, Andresen I (2020) An analytical method for evaluating and visualizing embodied carbon emissions of buildings. Build Environ 168:106476
3. Bahramian M, Yetilmezsoy K (2020) Life cycle assessment of the building industry: an overview of two decades of research (1995–2018). Energ Build 219:109917
4. Marinova S, Deetman S, van der Voet E, Daioglou V (2020) Global construction materials database and stock analysis of residential buildings between 1970–2050. J Clean Prod 247:119146

5. Wang Q, Tan Y, Mei Z (2020) Computational methods of acquisition and processing of 3D point cloud data for construction applications. Arch Comput Methods Eng 27:479–499
6. Mihić M, Sigmund Z, Završki I, Butković LL (2023) An analysis of potential uses, limitations and barriers to implementation of 3D scan data for construction management-related use—are the industry and the technical solutions mature enough for adoption. Buildings 13:1184
7. Liang X (2024) Application of 3D laser scanning technology in virtual reconstruction of existing building restoration. In: International conference on computer graphics, artificial intelligence, and data processing (ICCAID 2023). SPIE, pp 336–342
8. Antova G (2024) Portable laser scanning solutions for 3D modelling of large buildings. Int Arch Photogramm Remote Sens Spat Inf Sci XLVIII-4-W10-2024:13–19
9. Mariniuc AM, Cojocaru D, Manta LF, Dragomir A, Abagiu M Using 3D scanning techniques from robotic applications in the constructions domain. In: 2022 26th International conference on system theory, control and computing (ICSTCC), pp 170–175
10. Mora P, Garcia C, Ivorra E, Ortega M, Alcañiz ML (2024) Virtual experience toolkit: an end-to-end automated 3D scene virtualization framework implementing computer vision techniques. Sensors 24:3837
11. Barrile V, La Foresta F, Calcagno S, Genovese E (2024) Innovative system for BIM/GIS integration in the context of urban sustainability. Appl Sci 14:8704
12. Morel M, Balm S, Berden M, van Amstel WP (2020) Governance models for sustainable urban construction logistics: barriers for collaboration. Transp Res Procedia 46:173–180
13. Navares Vázquez JC. GitHub—JucaNavazReque/Reality-Mesher [Internet]. 12 Feb 2025. https://github.com/JucaNavazReque/Reality-Mesher
14. OECD. Measuring productivity—OECD manual [Internet]. 12 Feb 2025. www.oecd.org/en/publications/measuring-productivity-oecd-manual_9789264194519-en.html