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Article

Exploring the Potential of iPad-LiDAR Technology for Building Renovation Diagnosis: A Case Study

Pedro Mêda [1,*], Diego Calvetti [1] and Hipólito Sousa [2]

[1] CONSTRUCT/GEQUALTEC, Faculty of Engineering, Construction Institute, Porto University, 4200-465 Porto, Portugal
[2] CONSTRUCT/GEQUALTEC, Faculty of Engineering, Porto University, 4200-465 Porto, Portugal
* Correspondence: pmeda@fe.up.pt

Abstract: Digitalization and sustainability are twin trends in the construction industry (CI). Mobile devices are becoming more and more powerful, gaining the ability to support tasks that, until recently, were unthinkable. One example is LiDAR. The use of this technology embedded in tablets and smartphones brings new possibilities at a scan-to-BIM level. Given the commitment to circularity, waste audits will become mandatory for renovation projects. This is a heavy task that can benefit from existing processes and from digital technologies. This paper aims to demonstrate how everything is related and can be efficiently combined. The research convenes digital transition, green transition, circular economy, waste audit, LiDAR, and design processes' improvement. A mixed-methods approach aims to demonstrate how it is possible to establish digital waste audits and how these can become the core of the diagnosis process to be made during strategic definition or as part of the renovation design's initial actions. LiDAR technology embedded in mobile devices is worthy and can bring major improvements to the diagnosis phase. This will become more compliant with objectives set for digitalization and improved sustainability, contributing to the sector's twin digital and green transitions.

Keywords: LiDAR; buildings; renovation; construction 4.0; twin transition; diagnosis

Citation: Mêda, P.; Calvetti, D.; Sousa, H. Exploring the Potential of iPad-LiDAR Technology for Building Renovation Diagnosis: A Case Study. *Buildings* **2023**, *13*, 456. https://doi.org/10.3390/buildings13020456

Academic Editor: Muhammad Shafique

Received: 20 December 2022
Revised: 23 January 2023
Accepted: 29 January 2023
Published: 7 February 2023

1. Introduction

The construction industry (CI) transformation framework identifies many challenges at digitalization and sustainability levels [1]. Although these have been separately defined for the most part [2,3], both dimensions find common aspects and topics where one can support a better accomplishment of the other [1]. The increasing development and adoption of Light Detection and Ranging (LiDAR) technology in CI [4], mainly using mobile devices (e.g., tablets and smartphones), was chosen to prove this statement through the development of a specific case study. However, digitalization and sustainability challenges must integrate with existing processes, where shifts, suppressions, or additions will occur. The adoption of user-friendly and affordable technologies can bring benefits toward the sustainability requirements and improve existing processes, such as diagnosis actions to be made as part of the preliminary phases of buildings renovation projects. The ability to perceive the benefits, the constraints, and the competencies of how to implement such processes is found to be a key driver for innovation adoption [5–7].

The CI was a leader among the early group of adopters in information and communication technologies (ICTs), with the development and widespread adoption of structural analysis programs [8]. Changing from a manual to a computer-based process enhanced the structural dimensioning task and made it possible to concentrate the time and effort on analyzing the results, allowing for improvements, or streamlining corrections on the initial assumptions. The emergence of computer graphics in the 1980s was highly supported by many industries that shifted engineering drawings from boards to computers [9]. These two examples are meant to provide evidence of how the CI was at the forefront of ICT adoption in the last decades of the 20th century. This happened mainly because stakeholders could understand the technologies′ benefits; how they would fit into the processes; and what changes would be required in terms of investment, work organization, and competencies.

Due to its characteristics and internal challenges, the CI was less prepared to face the growing speed and rising of new technologies and concepts [10]. From a spearhead industry continuously implementing ICT, it became more reluctant, resisting new technologies in some cases or waiting for its consolidation in other fields [11]. Presently, it is imperative to increase the CI value chain digitalization and efficiency, given its economic, environmental, and social impacts [12]. The value chain to be considered needs to be broad, as construction products manufacturing and trade, logistics, and all stakeholders involved in the use phase of built objects fit in the construction life cycle [13]. From a stakeholder's perspective, the understanding of the CI must be expanded to range the actors involved in the mentioned processes. To strengthen these assumptions, some authors shifted the sector umbrella concept from CI to Architecture, Engineering and Construction, Owner, and Operator (AECOO) [14].

The digital technologies landscape is identified and has become part of most strategic and political documents addressing the digital transition, where Building Information Modeling (BIM), sensors, 3D scanning, mobile devices, virtual reality, and data analytics are among the most revealed [2,13,15,16]. As mentioned, AECOO highly impacts the environment. Although it is recognized as critical for countries' economies, it is also known that there are inefficiencies concerning energy waste, use of high-polluting processes, CO_2 production, and unsustainable resource consumption, both in terms of water and raw materials. In addition to improvements that can raise the environmental sustainability of the construction value chain and decrease its carbon footprint, it is also imperative to shift from a linear to a more circular approach to AECOO processes, built objects' life cycle, and its elements/components [17–19].

Previous research developed by the authors identified that digital technologies could improve processes and, at the same time, contribute to environmentally friendly and circular practices goals [1,20,21]. This was found to be a huge research field at that time, and it was identified as a gap. Recently, this turned into strategic actions and into a roadmap aiming to twin the digital and green transitions [22–24]. These previous studies focused on the use of digital data and on the requirements to improve construction products recovery, boosting reuse and recycling rates. This would later become part of the EU Circular Economy action plan update, strengthening the policy to deliver less waste and more value [25]. Emphasis was given to buildings renovation actions due to the short-term needs that are being assumed at the EU level with the Renovation Wave strategy [26] and due to the existence of guidelines for waste auditing, which practicality could be tested in real situations.

In parallel, the management of building renovation projects is typical, more challenging, and influenced by unforeseen elements that generate a high level of uncertainty and a wide range of technical and economic risks [27]. Most of these are connected to deficient as-built data of the existing object, including erroneous geometries and measurements, and deficient characterization, leading to "less accurate" design assumptions. Diagnosis actions are, consequently, critical for the success of these projects, both the ones made in the early phases before the renovation decision or performed during the early phases of design.

This study focuses on waste audit framed as part of the diagnosis action prior to building renovation supported by digital technologies, namely LiDAR embedded in mobile devices. An evaluation of its contribution to mitigate the mentioned risks by providing solid background 3D models to perform more accurate diagnosis and, at the same time, produce deliverables that can bring relevant outcomes at the circular economy level is the contribution to the body of knowledge. In parallel, answers are provided to the following questions: Is LiDAR technology useful for the waste audit process? Can the waste audit be a good practical example of how digital and green transitions can be merged? Should waste audits be part of the diagnosis?

An extensive building renovation use case was chosen to test the technology and how software solutions could support waste audit requirements. Although this was the primary motivation for the research, given the results, it became clear that there were conditions to explore a broader picture of LiDAR and supporting tools to improve building diagnosis action and its deliverables. Following this, a new orientation was set to determine how LiDAR technology embedded in mobile devices could improve the diagnosis action, accomplishing improved outcomes from traditional activities. The ability to perform 3D models during the diagnosis and, at the same time, identify and catalog existing materials promotes the sustainable products policy set by the EU circular economy action plan [25].

The present article contains six major sections, including this Introduction. The following outlines the method where the mixed methodologies approach is detailed. The literature review provides the knowledge base, where the main concepts under discussion are briefly framed. The narrative starts with twin transition goals to waste audit action and a summary of LiDAR technology to finalize with the scoping review on LiDAR application in renovation processes and using the mobile device "iPad" as part of the hardware. The Case Study section presents and explores all the actions taken on site, setting the background for the discussion and limitations where all crucial aspects are highlighted. Finally, the conclusion provides an overview of findings framed with future strategic actions to be pursued under this research topic.

Twin transition policy relies on the ability to use digital tools to improve processes and accomplish more circular and sustainable outcomes. This research provides a practical example of how to reach it by introducing innovations in an existing action, the diagnosis, and promoting an incremental improvement that can be more easily understood and adopted by stakeholders.

2. Method

Given the nature of the research, a mixed-methodologies approach [28] was set, combining a narrative review, a scoping review [29,30] using LiDAR with iPad devices for diagnosis as part of renovation projects, and a case study [31]. The aim was to set an incremental contribution [32] to the body of knowledge, evidencing a practical example of how digital and green transitions can be twinned. This is accomplished by exploring the LiDAR technology potential embedded in mobile devices and associated support tools to deliver waste audits. By doing it, one additional outcome is achieved, which is the introduction of comprehensive innovations in the diagnosis process that occurs before a building renovation.

Firstly, the scoping review was conducted and combined with relevant references from strategic documents addressing digital transition in the AECOO sector. The search was conducted between September 2022 and January 2023. The elaborated search queries to run on Thomson Reuters Web-of-Science (WoS) and Elsevier Scopus databases included "LiDAR" and "renovation", "LiDAR" and "iPad" (as the use of "mobile devices" as query evidenced lack of adhesion to the scope), and "LiDAR" and "diagnosis". Most results were out of the AECOO sector scope. The low number of results in all searches evidences the novelty of the research, namely when compared with other approaches and uses of LiDAR in the construction [4,33]. In this respect, its worth to highlight that it is recognized that other research works exist and were not identified due to the search queries selected. This does not limit the novelty of the subject and it is assumed as a limitation as the search queries selected are those more related to the defined scope.

As part of the GrowingCircle project [34] several case studies were performed using the same use case, a residential building with an ongoing deep renovation process. The intervention follow-up was used as a test bed to perform several activities with the scope of introducing digital technologies that could simultaneously enable a circular economy. LiDAR technology embedded in mobile devices was used as part of the framework to simulate an innovative waste audit process. A complete scan of all spaces/divisions from a sample apartment was made to acquire the needed data to feed material inventories [35].

Despite this main goal, other benefits were perceived during the process, namely the potential added value for the diagnosis action. A narrative review was then set to frame the most relevant concepts brought to the research. The findings, supported by the technology awareness and based on the case study results, aim to provide an incremental contribution to the body of knowledge by evidencing new uses for the still-in-infancy and growing adoption of LiDAR technology embedded in mobile devices.

3. Literature Review

This section aims to provide a knowledge base by presenting and detailing concepts briefly addressed in the Introduction section. An overview of the twin transitions EU strategic documents is made to understand the urgency and the objectives of adopting digitalization and achieving more sustainable processes in CI, where waste audit is key for the resource's consumption dimension. An overview of LiDAR technology, its growing development, and its uses in CI opens the way to present the results of the review on its use in diagnosis and renovation processes.

3.1. Twining Green and Digital

Until recently, digitalization and sustainability strategic documents were being developed, focusing on the specific objectives and topic-driven expected outcomes [2,33,36]. Although this was necessary, in what relates to AECOO, it became clear that there were relevant synergies and both dimensions could bring benefits to the other, namely by improving the speed of adoption, benefits realization, and goals accomplishment [1,37–39].

This realization is summarized in the 2022 Strategic Foresight Report on "Twinning the green and digital transitions in the new geopolitical context". Relating to the synergies, it is mentioned that Digital technologies could play a key role in achieving climate neutrality. On the other hand, Pursuing the green transition will also transform the digital sector [40]. This vision of the synergies was part of the GrowingCircle project assumptions, where through digital and circular data, it was intended to produce several proofs of concept on how circular economy could be boosted [23,34]. Research, awareness actions, stakeholders training, and case study-based demonstrations were part of the deliverables. Most focus on evidencing how the collection and management of data using digital technologies could support circular economy goals. In essence, a piece of data that traditionally would become part of a pdf document and that later would need to be consulted or copied for a sustainability-related action, by being digital, can be linked to a 3D model and managed/stored/linked for other purposes through the life cycle without getting lost [41]. From the Strategic Foresight Report and for this research, it is significant to highlight for future reading Section 4 addressing greening buildings with digitalization [24,40].

3.2. Waste Audit

The construction industry impacts the environment due to the transformations that it carries out. However, and more important for this context, are the resources that consume and the waste that produces. Transitioning from a linear to a circular value chain is demanding, and the way to accomplish it is by reusing or recycling most of the resources that are already part of the built environment [42]. The waste audit arises as a specific action to be taken before the demolition or renovation of buildings and infrastructures. It should be set as a part of the project to understand and quantify the types and amounts of elements and materials that will be deconstructed and/or demolished, where recommendations regarding their future handling should be issued [35].

The inventory of waste fractions and elements constitutes the core of the waste audit deliverables following the EU guidelines on this topic [43]. The material inventory must include the materials quantification in relevant units of measurement and type of material under several classifications, such as the European Waste Catalog (EWC); EURAL waste list; and data related to hazard ability, recycling, and reuse [44].

The data needed for waste audit have its roots in the design and construction phases and should be summarized in legacy documents. However, most times, these data are incomplete, are found to be wrong, or do not exist [45], meaning that on-site identification and quantification needs to be performed by using all time and cost-reasonable means.

3.3. The LiDAR Technology

Light Detection and Ranging (LiDAR) surveying uses a laser beam and radar features to collect information. The technology works by emitting lasers and measuring the time it takes for the light to return to the source. This technique came into use in the 1990s and made it possible to date the coordinates of the analyzed points concerning the emitter. LiDAR systems can work in static or mobile mode and generate dense point clouds from the environment in an accurate and quick way [46–48].

From 2016, when nano sensors and the Internet of nano things were identified as one of the Top 10 emerging technologies by the World Economic Forum, this technology experienced a great evolution, namely in the mobile version, becoming part of the tablets and mobile phones [9,38,39,47].

Mobile LiDAR systems first generate an accurate trajectory by using high-grade inertial systems combined with Simultaneous Localization and Mapping (SLAM) methodologies [49]. Once the trajectory is calculated, the LiDAR information, synchronized and bore-sighted, is inserted on the trajectory to obtain the complete 3D geometric information at mm-level accuracy. The volumes of generated data are very high, and the information is not structured in a useful way to perform engineering studies [46]. However, supporting tools with the ability to run algorithms and methods that efficiently extract the necessary information can make this technology a game changer. The technology is characterized by unique attributes, such as independence from external light for detection purposes, high resolution of detected points, and speed of operation. Due to its efficiency, speed, and flexibility, the LiDAR system stands out as one of the leading solutions for measuring various parameters in a wide range of activities [50].

LiDAR capabilities and supporting tools for mobile devices are only appearing now and already demonstrate huge application potential. It is easy to understand that, in the forthcoming years, the capabilities and uses will increase exponentially.

3.4. LiDAR for Diagnosis and Renovation Using iPad

LiDAR technology finds very different uses in the construction industry, namely for terrain modeling, infrastructures construction, or bridge surveillance [51–53]. In terms of hardware, specific LiDAR apparatus and sensors embedded in topography equipment or as part of unmanned aerial vehicles (UAVs) are among the most used [41,42]. LiDAR also finds several applications in heritage buildings combined with laser scan, where point clouds enable the detection of defects and singular shapes, among other things [45].

The use of LiDAR technology embedded in mobile devices for building indoors and for renovation processes constitutes the scope of the research. Although we anticipated the novelty of the topic, a review was performed by using a combination of "LiDAR and renovation", "LiDAR and iPad", and "LiDAR and diagnosis" concepts as a query. The searches were made by using the Elsevier Scopus and Thomson Reuters Web-of-Science (WoS) databases without any conditions or exclusions, except when explicitly mentioned.

Starting with "LiDAR" and "renovation", the Scopus database identified twelve results, one of which was duplicated. Three publications were excluded, as their scope was not CI, resulting in eight valid articles.

The WoS identified seven results, and four were duplicated from Scopus. The overall list of articles to analyze at this stage was eleven. The examination allowed the grouping of the results into clusters expressing the type of elements under research and/or the type of activity. Table 1 provides an overview of these works and their focus.

Table 1. Overview of the scope, topics, hardware used, and quantification of research works on "LiDAR" and "Renovation".

Scope/Construction Entity	Activity	Hardware	Works	References
Buildings	Creation of 3D models	Laser scan	3	[54–56]
Historical buildings	Threat detection, damage evaluation	Leica C-10 scanner, UAV	2	[57,58]
Pipelines/Wind turbine	Inspection	Radar, optical systems, Laser scan, UAV	4	[59–62]
Buildings	Object detection	Laser scan	1	[63]
Cartography	Measurement	UAV	1	[64]

Regarding "LiDAR" and "iPad", 24 results were identified in Scopus and 20 results in WoS, where 13 were duplicates. The overall list at this stage became 31. From these, 20 were excluded because the scope was not the CI. In this respect, it is worth highlighting that seven were focused on the topic "Forest". There was no overlap between the first search and the second. The remaining list with the relevant results was composed of 11 articles. As before, clustering was made to demonstrate the scope of the activities better. Table 2 provides an overview of the results.

Table 2. Overview of the scope, topics, hardware used, and quantification of research works on "LiDAR" and "iPad".

Scope/Construction Entity	Activity	Hardware	Works	References
Architectural objects	3D model, 3D point clouds, 3D rapid mapping	iPad Pro, iPhone 12 Pro, Huawei P30 Pro	2	[65,66]
Cultural Heritage/Archaeology	3D positional accuracy, 3D scanning, elements individualization	iPhone 12 Pro, iPad Pro, Faro X330, Zeb-Go	4	[67–70]
Indoor and outdoor environments	3D mapping, BIM	iPhone 12 Pro, iPad Pro, data collection equipment, Structure sensor	2	[71,72]
Geological fieldwork and mines	3D outcrop sharing, 3D scan/model, accuracy analysis	iPhone 12 Pro, iPad Pro	3	[73–75]

In what relates to "LiDAR" and "diagnosis", 42 results were identified in Scopus, applying the "Engineering" filter, and 14 results in WoS, with the "Civil engineering" filter. From these, 4 were duplicates, making a list of 52. From these, only 15 were considered, as the topic for the others was out of the CI scope. It deserves to be mentioned that autonomous vehicles were a topic that came up several times with this query, and despite some relationship to construction, a detailed analysis evidenced that the focus was on vehicles software more than road infrastructure. There was no overlap between this and the previous two searches. Clustering was performed to systematize the results, as evidenced in Table 3.

Table 3. Overview of the scope, topics, hardware used, and quantification of research works on "LiDAR" and "diagnosis".

Scope/Construction Entity	Activity	Hardware	Works	References
Structures (reinforced concrete, timber, masonry bridges, civil)	Risk/damage identification/assessment, 3D model, maintenance	Riegl LMS Z-390i	4	[76–79]
Historical buildings	Diagnosis, 3D model, risk assessment, damage identification	Z+F 3D laser scanner, OS1-64	5	[80–84]
Archeology/artwork	Monitoring, assessment		2	[85,86]
Wind turbine	Misalignments		1	[87]
Territory, soil, urban environment	Risk assessment, mobility, erosion		3	[88–90]

Few works fit the scope of the present research, and most of the results date from 2018 onward. Both facts evidence the novelty of the topic. Although some articles focus on different construction entities and activities, when the used hardware is mobile devices, significant contributions were identified. These are later explored in Sections 5 and 6.

4. Experiment/Case Study

4.1. Case Presentation and Objectives

A renovation project use case was selected to perform several case studies aiming to demonstrate how to improve process outcomes at circular economy and sustainability dimensions, through knowledge and the adoption of digital technologies. This was performed as part of the GrowingCircle project activities [34]. The project timeline covered most of the renovation (deconstruction/construction) phase, as well as the handover.

The use case is a residential building complex in the Matosinhos Municipality, Portugal, composed of seven buildings with four floors and each one with eight apartments (two per floor). Given the age, low energy performance, and poor living conditions, the design for the renovation was set to establish new envelope solutions (façade, windows, doors, and roofs); installation of new systems (water, electricity, communications, gas, etc.); and reconditioning of all interior elements, from finishings to kitchen and bathroom complete refurbishment.

Most of the apartments were similar and composed of an entrance with a corridor (Division 30) linking the remaining divisions. At its end, a small storeroom (Division 50) was set. The kitchen (Division 10), bathroom (Division 20), and laundry (Division 12) were close to each other and on one side together with the largest room (Division 01). Originally, the bathroom was divided with a wall and door to set a partition between the space for the toilet and bathtub and the space for the wash basin. This division was where more differences were identified from apartment to apartment. This situation led to adjustments in the scanning process, as is further detailed. On the other side, two smaller rooms (Divisions 02 and 03) and the living room (Division 11) made up the rest of the apartment spaces [91]. In total, each apartment is composed of 9 divisions (bathroom spaces might lead to 10), as presented in Figure 1.

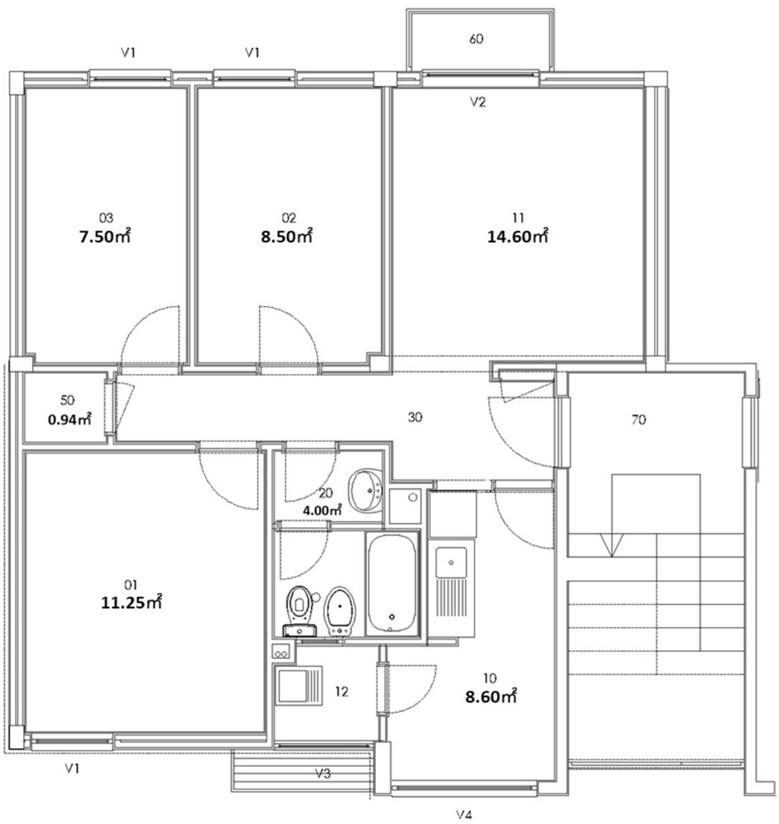

Figure 1. Sample apartment 2D drawing deliverable from the renovation design.

As there were few legacy documents and the renovation design deliverables (drawings and specifications) were found to have inaccuracies in their assumptions, one case study was adjusted to integrate the evaluation of the needed effort to develop a 3D model at apartment scale that could be postprocessed together with the existing 2D drawings to obtain a representative 3D building model. Taking advantage of LiDAR technology embedded in mobile devices and supporting tools (software), the same case study would try to evaluate what other processes could be supported as part of an extensive diagnosis to be performed during both the predesign and design phases. The main objective of the case study was to evaluate the ability to identify and quantify materials by using digital tools to support a waste audit action [35]. The case-study mindset was focused on delivering the waste audit key outcome, the material inventory.

4.2. Mobile Device Characterization

In 2020, Apple released the new iPad Pro and iPhone 12 Pro with a built-in LiDAR sensor. This type of sensor was mainly devoted to Augmented Reality (AR) applications and represented a considerable innovation in the market segment of tablets and smartphones [66].

As stated by Spreafico, the use of mobile devices with this type of sensor for metric survey purposes is obviously of high interest to the research community for both outdoor and indoor environments, especially when speed, portability, and cost-benefit optimization are essential requirements; and they are not always easy to meet using high-end surveying instruments [67].

The technical features, cost, and maneuverability of both devices represent an interesting solution when compared to other more consolidated range-based techniques already employed in various fields, such as Terrestrial Laser Scanning (TLS) or Time of Flight (TOF) cameras, to name a few [92].

For the case study, an iPad Pro 11-inch (3rd generation) device with 1TB was used. As a supporting tool and to make use of the LiDAR sensor to perform the scan-to-BIM process, the French software BIMeo was used [93]. One of its major innovations is the ability to deliver an IFC model. The interface with the operator supports this achievement.

4.3. Scan Process

Although all actions were performed during the construction phase, the objective was to simulate a scenario as close as possible to what it would be found before starting the renovation design or during its preliminary phases. Basically, this would correspond to the use phase of the building and its apartments. A moment in time was agreed together with the Owner and the Contractor to perform the scan. It was set for right after tenants had left the apartments and before deconstruction started. With this, the sample apartment would maintain most of its elements (some furniture included), which was found to be relevant to simulate potential real constraints. For waste audit purpose the objective is to achieve to a material inventory, meaning that spaces visibility and accessibility to collect relevant data, as the identification of solutions/products, materials, or their sizes/shapes must be assured. According to the guidelines, the inventory is composed by the “Type of Material”, “Material Identification”, “Waste code-EWC”, “Location”, “Quantity”, “Unit”, “Outlets” (possible and recommended), and “Pictures and notes” [35]. As it will be detailed, the scan and additional features allow a streamlined achievement of this deliverable. At the same time, other deliverables can gain advantages from this process.

As mentioned, the tool is set to perform single-division scans, and its gathering can be part of the intermediate postprocessing action. This can be made on-site or at the office. A project can be composed of one or a collection of several divisions.

Given the apartment′s organization and shapes (see Figure 1), it was decided to start with the corridor (Division 30) and then move to the living room (Division 11), following the division′s sequence ending in the laundry (Division 12).

As part of the software data input, wall thicknesses had to be measured and introduced. Door and window openings were used to obtain these measures. This is meant to support the geometrical definition of the division boundaries before the scan starts.

The following paragraphs detail all actions that must be performed to obtain a single division scan. Division 02 is used as a reference. As referred, to obtain the scan of the apartment, all divisions must be scanned.

The first step consists of a pre-scan using the LiDAR radar features. The space is "painted", providing the software with a preliminary understanding of the space configuration and geometries. The floor, ceiling, walls, and other elements should be "painted". This follows the division height definition by setting tags on the floor and the roof. The next step consists of scanning the walls from left to right, capturing all edges (Figure 2).

This process should be made by sections to better adjust to the division's real limits. By running this sequence, it is possible to obtain a 3D geometric shape of the division and with it the "Quantities". Depending on the area, configuration, and obstacles, the time taken for this action can highly vary. The process took around 2 min for Division 02, from the pre-scan start to the generation of the basic 3D model view. The scan can continue with the identification of objects, elements, and datasets, and this is data enrichment.

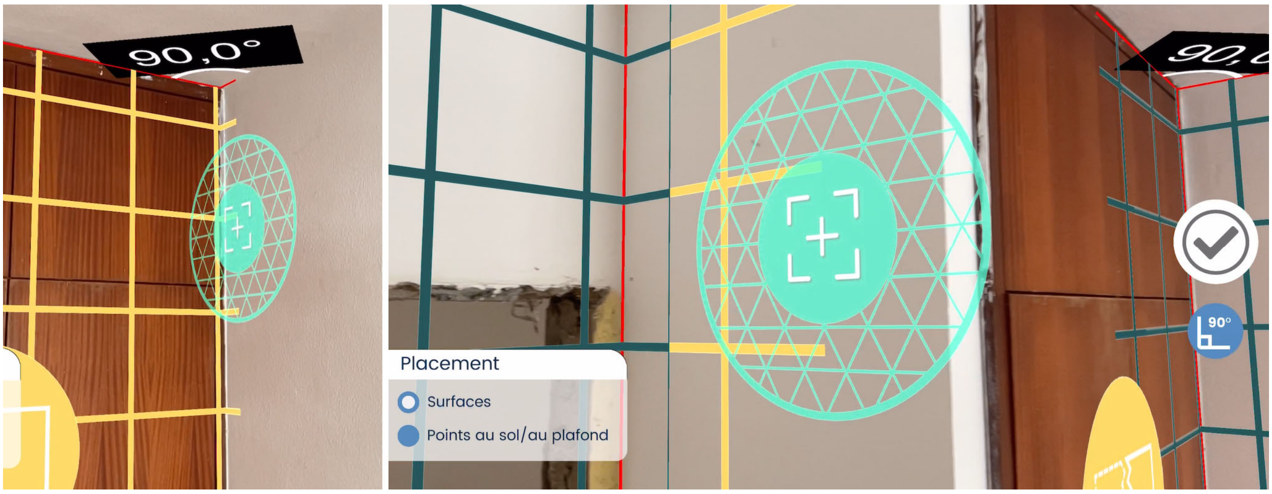

Figure 2. Scan-to-BIM process. Screen capture of wall scanning using iPad and BIMeo software [93].

4.4. Data Enrichment

Given the case-study objectives, the collection of details from all the apartment divisions was set as a requirement. Specifically, different singular elements were found to be meaningful for the material inventory in terms of weight, materials, and recycle/reuse outlets.

The tool provides several options to enrich the basic 3D model with additional data, namely the modeling of generic objects, photos capture and annotations. All were considered relevant for the waste audit as for the diagnosis actions.

Starting with the identification of generic objects, the tool provides a list of different objects, from doors and windows to systems appliances, such as taps, lighting fixtures, and furniture, among other things. By selecting the specific object, for example, a door, the "ifc_door" object type becomes part of the model data. The scan of the object can be made either using 2D or 3D geometry.

Depending on the division size, shape, and number of different objects to be identified, the time to perform the data enrichment action can vary. For the specific case of Division 02 (bedroom), four different object types were detailed, as presented in Table 4.

Table 4. Object scanned under the data enrichment process for Division 02 (bedroom).

Object	Type of Scan	Number of Scanned Items
Door	2D	1
Window	2D	1
Roller blind box	3D	1
Closet	2D	1

The functionalities of photo capture and annotations provide the ability to quickly acquire and/or detail specific aspects for postprocessing to occur at the office.

The photo capturing of elements that, although relevant, are more difficult to model, such as footers or elements where positioning will not be relevant for the future, for example, for electrical plugs, because all systems will be replaced and repositioned, constitutes a good example of this functionality potential.

Finally, annotations can be used to add to the model all kinds of data that are found to be needed. For the waste audit purpose and, as mentioned, the elements' composition/materials, potential outlets and the applicable EWC are relevant information that can be added to potentiate the material inventory delivering.

Figure 3 presents the complete 3D model from Division 02 performed on-site, where, in addition to the basic shape, the model was enriched with four different object types, two photos, and four annotations. The time spent to achieve this result was around 7 min.

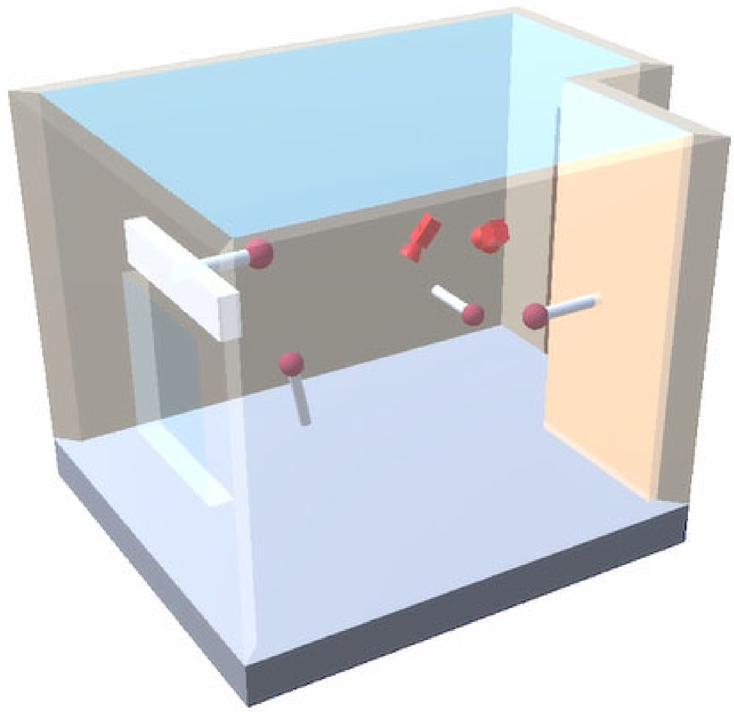

Figure 3. Three-dimensional model of Division 02 with all elements, photos, and annotations found meaningful for the waste audit process (screen shot from BIMeo software) [93].

Table 5 provides an overview of the timings and detail of the scan/data enrichment made for the different divisions. Specific aspects detected in different divisions are addressed in Section 5.

Table 5. Summary of the scan process of all divisions on the sample apartment.

Division	Area (m^2)	Object Types	Total Number	Photos	Annotations	Approximate Scan Time
Division 30	7.00	2	9	2	2	9:00
Division 11	14.60	3	3	2	1	6:00
Division 02	8.50	4	4	2	4	7:00
Division 03	7.50	4	4	2	2	6:00
Division 50	0.94	1	1	1	0	4:00
Division 01	11.25	4	9	0	3	6:00
Division 20	4.60	5	6	4	7	12:00
Division 10	8.60	5	5	2	2	10:00
Division 12	1.50	3	3	2	1	6:00

4.5. Postprocessing

Depending on the intended uses, the postprocessing phase can highly vary in terms of actions and time invested. The scope was to assess the waste amounts, the different materials, and their characterization to deliver a material inventory. Due to this, the postprocessing consisted mainly of gathering the different divisions to make the apartment, export of all elements, the adjustment of the BIM model, and the assessment and compilation of relevant data by using spreadsheets. All actions took around 4 h.

Other actions were developed out of the context of the case study as the copy to make the entire building and the modeling of additional elements, such as roofs and stairs. Only to provide a general idea of the effort, this took around one working day assured by a professional with competencies in 3D modeling software, such as Autodesk REVIT.

The gathering of the different divisions was made in the tool. All divisions must be placed on the project layout and positioned either in a 2D plant or in 3D. Figure 4 provides an overview of the final apartment layout.

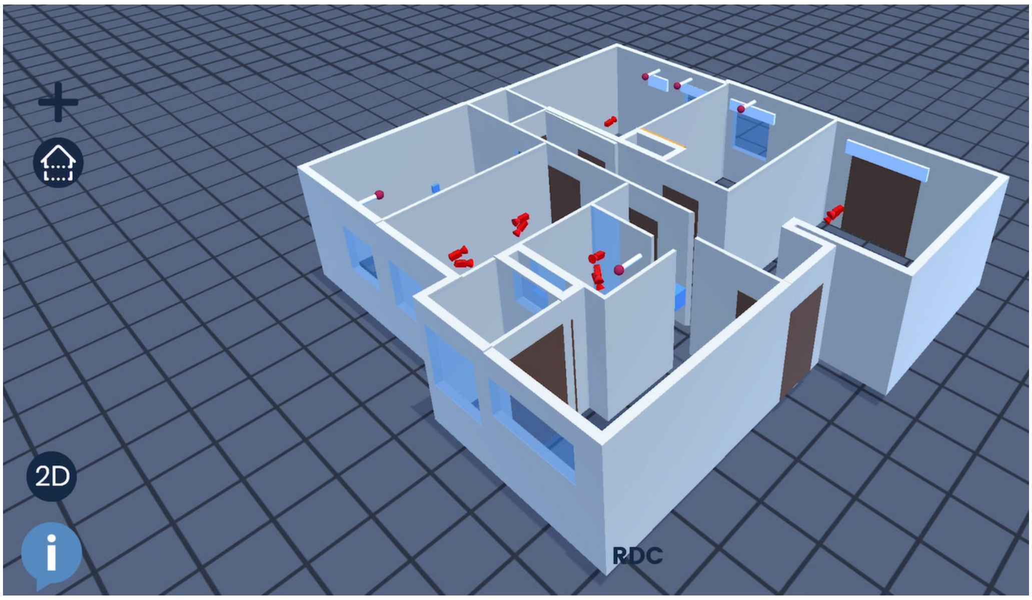

Figure 4. The image on the 3D model of the sample apartment with all divisions, objects, photos, and annotations (screen shot from BIMeo software) [93].

The export of the model follows, as well as all relevant associated elements, such as spreadsheets with quantities, 2D drawings, inspection reports with the photos and annotations, the IFC 3D model in IFC2 × 3 and IFC4 versions, and the building SMART BIM collaboration format (BCF) files.

4.6. Remarks

As evidenced, there can be significant differences in the timings to perform the scan of an entire apartment. Depending on the intended purposes that must be defined before going on-site, the time spent scanning each division will vary depending on the shape and number, types, and constraints of access/visualization of the different existing elements. When possible, before the scan, a general overview of the building should be made to obtain a clear picture of the object and its singularities/constraints, select the sample to be scanned, and set the best strategy for active development.

A preliminary assessment of the thickness of the different walls is found to be relevant before starting the scan. This action should be taken at the office, followed by confirmation on-site.

Overall, the scan-to-BIM process in the context of this case study took around one working day, including preliminary assessments, scan, and data enrichment of the different divisions, followed by at-office postprocessing.

As mentioned, the case study was entirely developed during the construction phase. However, it was possible to simulate the ideal situation, meaning the situation that would be found in the real diagnosis phase, where tenants had left the apartment, and most of the elements were still in place.

Other data collections relevant to diagnosis could have been gathered if applicable and depending on the requirements.

5. Findings and Limitations

Although in infancy, LiDAR sensors embedded in mobile devices have all the conditions to be an AECOO game changer in the forthcoming years, increasing the efficiency of the scan-to-BIM process and reducing the involved costs [72]. However, despite the possibilities and potential, a good definition of the intended purposes is key to evaluating the needs in terms of postprocessing effort, competencies, and the nowadays still existing technological limitations when using this type of hardware [46].

For the waste audit purpose, the accuracy is acceptable, namely when legacy data, such as 2D drawings, are lacking. The ability to combine this with notes for the materials/waste recognition makes it not just applicable but a valuable resource for process efficiency.

As detailed, the scan-to-BIM of the case-study sample apartment, consisting of nine divisions with an approximate area of 70 m^2, and performed by a senior civil engineer with limited skills in the technology and tool, took around one hour and ten minutes.

Regarding hardware performance, the process is demanding, meaning that the device battery is consumed by more than half to perform the scan and data enrichment.

Competencies of the operator are found to be relevant, namely for the accuracy of tagging the correct geometry of the elements and for dealing with potential constraints regarding LiDAR usability in tight or dark spaces. This particular aspect is already being considered in other uses [94], and it is found to be a relevant field for future research. Small divisions can constitute an obstacle for the scan, given the inability to obtain the needed minimum optimal distance for the space and its elements to be scanned. In perfect conditions, it should be possible to see an entire segment at the height of the walls. This was not the situation in most of the case-study divisions. On the other hand, LiDAR technology might have difficulties in capturing shapes when the distance is above 4 m. This situation was observed in other case studies performed by authors; however, in this one, it did not occur.

Light conditions are key for the scan process to work. The LiDAR sensor has difficulties in capturing shapes when light conditions are poor or when severe contrasts exist. Regarding this second aspect, most situations can be solved by adjusting the operator's positioning when performing the scan. In addition, it is relevant to detail the constraints faced by Divisions 20 and 50. Starting with Division 20 (bathroom), the existence of a wall and door to separate the toilet and bathtub from the wash basin required splitting the division in two. To make the scan possible in such a confined area, it was necessary to use all the space from one division to scan the other. This was the only way of reaching all of the needed angles. In Division 50, the narrow space and mainly the poor light conditions made it difficult to perform the scan. Additional lights using lanterns and a scan process performed from the outside (the corridor) were the efficient solutions to overcome the obstacles.

As mentioned, the tool provides the ability to take photos and introduce annotations. In what relates to this second functionality, it is relevant to state that specific checklists can be built to serve specific purposes. Following meetings with the BIMeo team, where several potential innovations were discussed, the introduction of a specific feature to improve the introduction of data related to the waste auditing process was found to be interesting and a way to streamline even more the productivity of the on-site process.

At this level, the operator competencies are also relevant, namely for the identification of materials and products, the applicable waste codes [95], and potential outlets to be better defined during design.

The use of mobile devices with embedded LiDAR sensors for waste auditing is a good example of how digital and green transitions can be twinned. Given the circular economy goals, the waste audit will be more and more relevant, and the digital tools will prove to contribute to streamlining the accomplishment of the objectives. In addition, all of this only makes sense if integrated with existing processes, namely the diagnosis action. It will become more demanding, but, at the same time, it will lead to improved benefits for the value-chain and construction process by bringing a proficient IFC model based on a scan-to-BIM and metadata to support improved eco-design options earlier.

In addition, this innovative process suits an incremental learning philosophy where stakeholders can easily perceive the challenges and benefits, becoming more prone to changes and adoption.

6. Conclusions

LiDAR technology, as evidenced, already has very different applications. However, its use embedded in mobile devices and for buildings' renovation processes is still in its infancy. As the review demonstrates, few studies exist.

The technology revealed very interesting capabilities, and it is possible to state that the topic will continue to gain traction in the next years. LiDAR embedded in mobile devices provides a quick and less expensive way of performing scan-to-BIM actions, as demonstrated in the case study. The benefits, namely when compared with laser scan point clouds, are the speed of scanning and the postprocessing effort on 3D modeling tools to achieve a proficient BIM model.

Future studies need to be developed regarding the accuracy, and the data-enrichment process will heavily rely on the operator's abilities and experience in performing actions such as waste audits and/or diagnosis. However, it must be recognized that 2D drawings from the existing built object constitute only an approximation of the existing reality. The achieved model, with all its imprecisions, will most times be more reliable than legacy documents if these exist.

Depending on the BIM used to be set for the renovation process, the 3D model might need more postprocessing on additional modeling tools to provide an outcome adjusted to the intended objectives. In this respect, and when they exist, the use of legacy documents can support the achievement of a more consistent deliverable.

In what relates to waste auditing to be performed before building renovation, LiDAR technology combined with the software tools in mobile devices such as the iPad provides the needed features to perform streamlined quantification of the elements/materials amounts. The ability to set comments and capture pictures enables on-site identification and parametrization of materials/EWC/potential outlets, among other things. The ability of the software to automatically deliver these elements in IFC brings an additional advantage to the entire process.

These features overlap with actions that must be performed as part of the diagnosis to occur before starting the design phase or as part of this phase's initial actions within a renovation construction process.

The ability to perform an agile scan-to-BIM of a building indoors by using LiDAR technology and the combined use of the abovementioned features serves entirely the purpose of what is expected to be achieved with a detailed diagnosis.

Considering the objectives set on the EU Circular Economy action plan and on the Renovation Wave strategy, and assuming the use of digital supporting technologies, waste audits gain relevance as a key step in an innovative diagnosis action. The definition of potential outlets for the different elements/products will provide contributions to sustainability by supporting design decisions, namely if there are elements to be reused.

Future research will concentrate on further exploring the potentialities and limitations of the LiDAR technology embedded in mobile devices and supporting tools in different contexts. In addition, it envisaged the establishment of a more complete framework of integrated tasks to be considered as part of an innovative diagnosis.

With this environment, the diagnosis, a key action to occur before all renovations, will become compliant with the objectives set for digitalization and improved sustainability of the construction industry, contributing to twin the sector digital and green transitions.

Author Contributions: Conceptualization, D.C. and P.M.; methodology, P.M.; software, P.M.; validation, H.S., D.C. and P.M.; formal analysis, D.C.; investigation, P.M.; resources, P.M.; data curation, P.M.; writing—original draft preparation, P.M.; writing—review and editing, D.C. and H.S.; visualization, D.C.; supervision, H.S.; project administration, H.S. and P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Project GrowingCircle-Integrated Data for Efficient and Sustainable Construction, funded by the European Economic Area (EEA) Financial Mechanism 2014–2021; Environment, Climate Change and Low Carbon Economy Programme; and Base Funding of the CONSTRUCT—Instituto de I&D em Estruturas e Construções—funded by national funds through the FCT/MCTES (PIDDAC): UIDB/04708/2020.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank all stakeholders involved in the case study, namely the owner, Município de Matosinhos/MatosinhosHabit; EM; and the contractor, Befebal. Would like to thank the support from the BIMeo team.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mêda, P.; Hjelseth, E.; Calvetti, D.; Sousa, H. Enabling circular construction information flows using data templates—Conceptual frameworks based on waste audit action. In Proceedings of the 2021 EC3—European Conference on Computing in Construction, Online, 19–28 July 2021; pp. 398–405. [CrossRef]
2. European Construction Sector Observatory. Digitalisation in the Construction Sector. 2021. Available online: https://ec.europa.eu/docsroom/documents/45547/attachments/1/translations/en/renditions/native (accessed on 20 September 2022).
3. European Commission. *The European Green Deal*; European Commission: Brussels, Belgium, 2019.
4. Chen, X.; Chang-Richards, A.Y.; Pelosi, A.; Jia, Y.; Shen, X.; Siddiqui, M.K.; Yang, N. Implementation of technologies in the construction industry: A systematic review. *Eng. Constr. Archit. Manag.* **2022**, *29*, 3181–3209. [CrossRef]
5. Derenzi, D.; de Sousa, P.S.; de Oliveira, S.A.; Herdeiro, M.A.N.; Albernaz, J.R.; Valadares, A. A successful approach in integrating people, process, and technology inside collaborative environments: A practical view of challenges and lessons learned. *Digit. Energy Conf. Exhib.* **2009**, *2009*, 268–277. [CrossRef]
6. Karmakar, A.; Delhi, V.S.K. Construction 4.0: What we know and where we are headed? Next Generation ICT—How distant is ubiquitous computing? *J. Inf. Technol. Constr.* **2021**, *26*, 526–545. [CrossRef]
7. Harty, C. Implementing innovation in construction: Contexts, relative boundedness and actor-network theory. *Constr. Manag. Econ.* **2008**, *26*, 1029–1041. [CrossRef]
8. Turk, Ž. Construction 4.0—Digital Transformation of One of the Oldest Industries. *Econ. Bus. Rev.* **2019**, *21*, 393–410. [CrossRef]
9. Duhovnik, J. *Računalniško Projektiranje (CAD) Gradbenih Konstrukcij*; Fakulteta: Ljubljana, Slovenia, 1984. Available online: https://plus.cobiss.net/cobiss/si/sl/bib/47410 (accessed on 29 November 2022).

10. Forum, W.E. *Shaping the Future of Construction—A Breakthrough in Mindset and Technology*; World Economic Forum: Geneva, Switzerland, 2016. Available online: https://www.weforum.org/reports/shaping-the-future-of-construction-inspiring-innovators-redefine-the-industry (accessed on 26 September 2022).
11. Forbes, L.H.; Ahmed, S.M. Construction Integration and Innovation Through Lean Methods and E-Business Applications. In Proceedings of the Contruction Research Congress, Winds of Change: Integration and Innovation in Construction, Proceedings of the Congress, Honolulu, HI, USA, 19–21 March 2003; pp. 337–346. [CrossRef]
12. European Construction Sector Observatory. *Building Information Modelling in the EU Construction Sector*; European Construction Sector Observatory: Brussels, Belgium, 2019. Available online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiPpvmmjP77AhWLTaQEHVHbCPUQFnoECA0QAQ&url=https%3A%2F%2Fwww.efbww.eu%2Fstream%2Fd7c22ce7-4297-40a9-ae3c-2ada75333c83&usg=AOvVaw3Y68j1bUB6nh9nmCQbpmIQ (accessed on 26 September 2022).
13. Staff, C. *Scenarios for a Transition Pathway for a Resilient, Greener and More Digital Construction Ecosystem (Ares(2021)7679109) Final)*; European Commission: Brussels, Belgium, 2021.
14. Project, S. *Towards a Unified Reference Architecture in AECOO Industry*; Technical Insight: Barcelona, Spain, 2020. Available online: https://sphere-project.eu/publication-results/project-deliverables/ (accessed on 29 November 2022).
15. Calvetti, D.; Sanhudo, L.; Mêda, P.; Martins, J.P.; Gonçalves, M.C.; Sousa, H. Construction Tasks Electronic Process Monitoring: Laboratory Circuit-Based Simulation Deployment. *Buildings* **2022**, *12*, 1174. [CrossRef]
16. Calvetti, D.; Mêda, P.; Sousa, H.; Gonçalves, M.C. Human Data Interaction in Sensored Sites, Challenges of the Craft Workforce Dimension. In Proceedings of the 2021 European Conference on Computing in Construction, Rhodes, Greece, 19–28 July 2021; pp. 173–180. [CrossRef]
17. Quiñones, R.; Llatas, C.; Montes, M.V.; Cortés, I. A multiplatform bim-integrated construction waste quantification model during design phase. The case of the structural system in a spanish building. *Recycling* **2021**, *6*, 62. [CrossRef]
18. Calvetti, D.; Goncalves, M.; Vahl, F.; Meda, P.; de Sousa, H. Labour productivity as a means for assessing environmental impact in the construction industry. *Environ. Eng. Manag. J.* **2021**, *5*, 781–790. [CrossRef]
19. Kovacic, I.; Honic, M.; Sreckovic, M. Digital platform for circular economy in aec industry. *Eng. Proj. Organ. J.* **2020**, *9*, 1–16. [CrossRef]
20. Çetin, S.; De Wolf, C.; Bocken, N. Circular digital built environment: An emerging framework. *Sustainability* **2021**, *13*, 6348. [CrossRef]
21. Mêda, P.; Calvetti, D.; Hjelseth, E.; Sousa, H. Incremental Digital Twin Conceptualisations Targeting Data-Driven Circular Construction. *Buildings* **2021**, *11*, 554. [CrossRef]
22. Magalhães, P.M.; Calvetti, D.; Kifokeris, D.; Kassem, M. A Process-Based Framework for Digital Building Logbooks. In Proceedings of the 2022 European Conference on Computing in Construction, Rhodes, Greece, 24–26 July 2022; p. 8. [CrossRef]
23. Nativi, S.; Delipetrev, B.; Craglia, M. *Destination Earth Survey on "Digital Twins" Technologies and Activities, in the Green Deal Area*; Publications Office of the European Union: Luxembourg, 2020. [CrossRef]
24. Muench, F.; Stoermer, S.; Jensen, E.; Asikainen, K.; Salvi, T.; Scapolo, M. *Towards a Green and Digital Future*; Publications Office of the European Union: Brussels, Belgium, 2022. [CrossRef]
25. Comission, E. *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*; European Commission: Brussels, Belgium, 2020.
26. European Commission. *A Renovation Wave for Europe*; European Commission: Brussels, Belgium, 2020.
27. Uotila, U.; Saari, A.; Junnonen, J.-M. Investigating the barriers to laser scanning implementation in building refurbishment. *J. Inf. Technol. Constr.* **2021**, *26*, 249–262. [CrossRef]
28. Cameron, S.; Sankaran, R. Mixed Methods Research in Project Management. In *Design Methods and Practices for Research of Project Management*; Gower, B.A., Pasian, B., Eds.; Routledge: New York, NY, USA, 2017; pp. 273–285. [CrossRef]
29. Sovacool, B.K.; Axsen, J.; Sorrell, S. Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design. *Energy Res. Soc. Sci.* **2018**, *45*, 12–42. [CrossRef]
30. Arksey, H.; O'Malley, L. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol. Theory Pract.* **2005**, *8*, 19–32. [CrossRef]
31. Fellows, R.; Liu, A. *Research Methods for Construction*; Wiley-Blac: Oxford, UK, 2022.
32. Hallgren, M. Novel or Incremental Contributions: The Construction of Research Questions. In *Design Methods and Practices for Research of Project Management*; Gower, B.A., Pasian, B., Eds.; Routledge: New York, NY, USA, 2017; pp. 107–118. [CrossRef]
33. O'Donnell, J.; Truong-Hong, L.; Boyle, N.; Corry, E.; Cao, J.; Laefer, D.F. LiDAR point-cloud mapping of building façades for building energy performance simulation. *Autom. Constr.* **2019**, *107*, 102905. [CrossRef]
34. da Construção, I.-I. GrowingCircle Project—Building Case Study. Available online: https://growingcircle.netlify.app/cases/matosinhoshabit (accessed on 20 September 2022).
35. European Commission. *Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings. UE Construction and Demolition Waste Management*; European Commission: Brussels, Belgium, 2018. Available online: https://ec.europa.eu/docsroom/documents/31521/attachments/1/translations/en/renditions/native (accessed on 20 July 2022).
36. European Construction Sector Observatory. *EU Construction Sector: In Transition towards Circular Economy*; European Construction Sector Observatory: Brussels, Belgium, 2019.

37. Liu, Z.; Lu, Y.; Shen, M.; Peh, L.C. Transition from building information modeling (BIM) to integrated digital delivery (IDD) in sustainable building management: A knowledge discovery approach based review. *J. Clean. Prod.* **2021**, *291*, 125223. [CrossRef]
38. De Wolf, C.; Cordella, M.; Dodd, N.; Byers, B.; Donatello, S. Whole life cycle environmental impact assessment of buildings: Developing software tool and database support for the EU framework Level(s). *Resour. Conserv. Recycl.* **2023**, *188*, 106642. [CrossRef]
39. Çetin, S.; Gruis, V.; Straub, A. Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. *Resour. Conserv. Recycl. Adv.* **2022**, *15*, 200110. [CrossRef]
40. European Parliament and European Union Council. *2022 Strategic Foresight Report—Twinning the Green and Digital Transitions in the New Geopolitical Context (COM(2022) 289 Final)*; European Parliament and European Union Council: Brussels, Belgium, 2022.
41. Centre for Digital Built Britain; Jalia, A.; Bakker, R.; Zomer, T.; Lamb, K.; Boulton, C.; Neely, A.; Repository, I.; Infrastructure, S. *Capability Framework and Research Agenda for a Digital Built Britain*; Centre for Digital Built Britain: Cambridge, UK, 2019. [CrossRef]
42. Joensuu, T.; Edelman, H.; Saari, A. Circular economy practices in the built environment. *J. Clean. Prod.* **2020**, *276*, 124215. [CrossRef]
43. Tsay, G.S.; Staub-French, S.; Poirier, É. BIM for Facilities Management: An Investigation into the Asset Information Delivery Process and the Associated Challenges. *Appl. Sci.* **2022**, *12*, 9542. [CrossRef]
44. European Commission. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. *Off. J. Eur. Union* **2018**, *14*, L-150/109-140. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0851 (accessed on 20 July 2022).
45. Saura-Gómez, P.; Spairani-Berrio, Y.; Huesca-Tortosa, J.A.; Spairani-Berrio, S.; Rizo-Maestre, C. Advances in the restoration of buildings with lidar technology and 3d reconstruction: Forged and vaults of the refectory of santo domingo de orihuela (16th century). *Appl. Sci.* **2021**, *11*, 8541. [CrossRef]
46. Díaz-Vilariño, L.; Tran, H.; Frías, E.; Balado, J.; Khoshelham, K. 3D Mapping of Indoor and Outdoor Environments Using Apple Smart Devices. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2022**, *43*, 303–308. [CrossRef]
47. Stein, S. Lidar is One of the iPhone and iPad Pro's Coolest Tricks: Here's What Else it Can Do. CNET—Your Guide to a Better Future. 2022. Available online: https://www.cnet.com/tech/mobile/lidar-is-one-of-the-iphone-ipad-coolest-tricks-its-only-getting-better/ (accessed on 26 September 2022).
48. Di Stefano, F.; Chiappini, S.; Gorreja, A.; Balestra, M.; Pierdicca, R. Mobile 3D scan LiDAR: A literature review. *Geomat. Nat. Hazards Risk* **2021**, *12*, 2387–2429. [CrossRef]
49. Lv, D.; Ying, X.; Cui, Y.; Song, J.; Qian, K.; Li, M. Research on the technology of LIDAR data processing. In Proceedings of the 1st International Conference on Electronics Instrumentation & Information Systems (EIIS 2017), Harbin, China, 3–5 June 2017; pp. 1–5. [CrossRef]
50. Lopac, N.; Jurdana, I.; Brnelić, A.; Krljan, T. Application of Laser Systems for Detection and Ranging in the Modern Road Transportation and Maritime Sector. *Sensors* **2022**, *22*, 5946. [CrossRef] [PubMed]
51. Soilán, M.; Nóvoa, A.; Sánchez-Rodríguez, A.; Justo, A.; Riveiro, B. Fully automated methodology for the delineation of railway lanes and the generation of IFC alignment models using 3D point cloud data. *Autom. Constr.* **2021**, *126*, 103684. [CrossRef]
52. Ren, Y.; Ai, C.; Lu, P.; Dai, Z.; Wang, H. An Automated Rail Extraction Framework for Low-Density LiDAR Data Without Sensor Configuration Information. *IEEE Sensors J.* **2022**, *22*, 13234–13243. [CrossRef]
53. Puri, N.; Turkan, Y. Bridge construction progress monitoring using lidar and 4D design models. *Autom. Constr.* **2020**, *109*, 102961. [CrossRef]
54. Xiong, X.; Adan, A.; Akinci, B.; Huber, D. Automatic creation of semantically rich 3D building models from laser scanner data. *Autom. Constr.* **2013**, *31*, 325–337. [CrossRef]
55. Benarab, D.; Derigent, W.; Brie, D.; Bombardier, V.; Thomas, A. *All-Automatic 3D BIM Modeling of Existing Buildings*; Springer International Publishing: Cham, Switzerland, 2018; Volume 540. [CrossRef]
56. Hajeb, M.; Karimzadeh, S.; Matsuoka, M. SAR and LIDAR datasets for building damage evaluation based on support vector machine and random forest algorithms—A case study of Kumamoto earthquake, Japan. *Appl. Sci.* **2020**, *10*, 8932. [CrossRef]
57. Błaszczak-Bąk, W.; Suchocki, C.; Janicka, J.; Dumalski, A.; Duchnowski, R.; Sobieraj-Żłobińska, A. Automatic threat detection for historic buildings in dark places based on the modified OPTD method. *ISPRS Int. J. Geo-Information* **2020**, *9*, 123. [CrossRef]
58. Dedík, L.; Minaroviech, J. Project of the digital monuments funds: Digitization of the cultural heritage of Slovakia. *Stud. Digit. Herit.* **2017**, *1*, 590–606. [CrossRef]
59. Ékes, C. Inspecting Twin 42 Reinforced Concrete Pipes with Pipe Penetrating Radar Supplemented by LiDAR. In Proceedings of the Pipelines 2021: Planning—Proceedings of Sessions of the Pipelines 2021 Conference, Online, 3–6 August 2021; pp. 236–241. [CrossRef]
60. Kumar, G.A.; Patil, A.K.; Kang, T.W.; Chai, Y.H. Sensor fusion based pipeline inspection for the augmented reality system. *Symmetry* **2019**, *11*, 1325. [CrossRef]
61. Aijazi, A.K.; Malaterre, L.; Trassoudaine, L.; Chateau, T.; Checchin, P. Automatic detection and modeling of underground pipes using a porTable 3D LiDAR system. *Sensors* **2019**, *19*, 5345. [CrossRef] [PubMed]
62. Car, M.; Markovic, L.; Ivanovic, A.; Orsag, M.; Bogdan, S. Autonomous Wind-Turbine Blade Inspection Using LiDAR-Equipped Unmanned Aerial Vehicle. *IEEE Access* **2020**, *8*, 131380–131387. [CrossRef]

63. Mansor, H.; Shukor, S.A.A.; Wong, R. An overview of object detection from building point cloud data. *J. Phys. Conf. Ser.* **2021**, *1878*, 012058. [CrossRef]
64. Orsulic, J.; Milijas, R.; Batinovic, A.; Markovic, L.; Ivanovic, A.; Bogdan, S. Flying with Cartographer: Adapting the Cartographer 3D Graph SLAM Stack for UAV Navigation. In Proceedings of the AIRPHARO 2021—1st AIRPHARO Workshop on Aerial Robotic Systems Physically Interacting with the Environment, Biograd na Moru, Croatia, 4–5 October 2021. [CrossRef]
65. Costantino, D.; Vozza, G.; Pepe, M.; Alfio, V.S. Smartphone LiDAR Technologies for Surveying and Reality Modelling in Urban Scenarios: Evaluation Methods, Performance and Challenges. *Appl. Syst. Innov.* **2022**, *5*, 63. [CrossRef]
66. Spreafico, A.; Chiabrando, F.; Losè, L.T.; Tonolo, F.G. The ipad pro built-in lidar sensor: 3D rapid mapping tests and quality assessment. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2021**, *43*, 63–69. [CrossRef]
67. Losè, L.T.; Spreafico, A.; Chiabrando, F.; Tonolo, F.G. Apple LiDAR Sensor for 3D Surveying: Tests and Results in the Cultural Heritage Domain. *Remote. Sens.* **2022**, *14*, 4157. [CrossRef]
68. Meegan, E.; Murphy, M.; Corns, A.; Shaw, R.; Lionáin, C.N.; Keenaghan, G. Tripping the light fantastic: Using light-based techniques to digitally document megalithic architecture. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2022**, *46*, 373–379. [CrossRef]
69. Balado, J.; Frías, E.; González-Collazo, S.M.; Díaz-Vilariño, L. *New Trends in Laser Scanning for Cultural Heritage*; Springer: Singapore, 2022; Volume 258. [CrossRef]
70. Murtiyoso, A.; Grussenmeyer, P.; Landes, T.; Macher, H. First assessments into the use of commercial-grade solid state lidar for low cost heritage documentation. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2021**, *43*, 599–604. [CrossRef]
71. Díaz-Vilariño, L.; González-Jorge, H.; Martínez-Sánchez, J.; Lorenzo, H. Automatic LiDAR-based lighting inventory in buildings. *Meas. J. Int. Meas. Confed.* **2015**, *73*, 544–550. [CrossRef]
72. Li, Y.; Li, W.; Tang, S.; Darwish, W.; Hu, Y.; Chen, W. Automatic indoor as-built building information models generation by using low-cost RGB-D sensors. *Sensors* **2020**, *20*, 293. [CrossRef]
73. Tavani, S.; Billi, A.; Corradetti, A.; Mercuri, M.; Bosman, A.; Cuffaro, M.; Seers, T.; Carminati, E. Smartphone assisted fieldwork: Towards the digital transition of geoscience fieldwork using LiDAR-equipped iPhones. *Earth-Science Rev.* **2022**, *227*, 103969. [CrossRef]
74. Birch, C.; Olivier, A. Narrow, tabular stope 3d scanning in deep-level gold mines using an ipad pro lidar. In Proceedings of the 27th International Mining Congress and Exhibition of Turkey, IMCET 2022, Antalya, Turkey, 22–25 March 2022; pp. 658–669.
75. Luetzenburg, G.; Kroon, A.; Bjørk, A.A. Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences. *Sci. Rep.* **2021**, *11*, 1–9. [CrossRef]
76. Valla, M.; Gueguen, P.; Augère, B.; Goular, D.; Perrault, M. Remote Modal Study of Reinforced Concrete Buildings Using a Multipath Lidar Vibrometer. *J. Struct. Eng.* **2015**, *141*, D4014005. [CrossRef]
77. Bertolini-Cestari, C.; Chiabrando, F.; Invernizzi, S.; Marzi, T.; Spanò, A. Terrestrial laser scanning and settled techniques: A support to detect pathologies and safety conditions of timber structures. *Adv. Mater. Res.* **2013**, *778*, 350–357. [CrossRef]
78. Sánchez-Rodríguez, A.; Riveiro, B.; Conde, B.; Soilán, M. Detection of structural faults in piers of masonry arch bridges through automated processing of laser scanning data. *Struct. Control. Health Monit.* **2018**, *25*, e2126. [CrossRef]
79. Murakami, T.; Saito, N.; Michikawa, T.; Komachi, Y.; Sakasita, M.; Kogure, S.; Kase, K.; Wada, S.; Midorikawa, K. Extending the exposure time in high-resolution mobile tunnel lidar. *Opt. InfoBase Conf. Pap.* **2019**, *Part F140*, 7281.
80. Costamagna, E.; Quintero, M.S.; Bianchini, N.; Mendes, N.; Lourenço, P.B.; Su, S.; Paik, Y.M.; Min, A. Advanced non-destructive techniques for the diagnosis of historic buildings: The Loka-Hteik-Pan temple in Bagan. *J. Cult. Herit.* **2020**, *43*, 108–117. [CrossRef]
81. Akhlaghi, M.M.; Bose, S.; Mohammadi, M.E.; Moaveni, B.; Stavridis, A.; Wood, R.L. Post-earthquake damage identification of an RC school building in Nepal using ambient vibration and point cloud data. *Eng. Struct.* **2021**, *227*, 111413. [CrossRef]
82. Marzouk, M. Using 3D laser scanning to analyze heritage structures: The case study of egyptian palace. *J. Civ. Eng. Manag.* **2020**, *26*, 53–65. [CrossRef]
83. Cardani, G.; Angjeliu, G. Integrated use of measurements for the structural diagnosis in historical vaulted buildings. *Sensors* **2020**, *20*, 4290. [CrossRef]
84. Aristipini, P.; Colao, F.; Fantoni, R.; Fiorani, L.; Palucci, A. Scanning lidar fluorosensor for cultural heritage diagnostics. *Adv. Laser Technol.* **2005**, *5850*, 196–203. [CrossRef]
85. Chen, F.; Lasaponara, R.; Masini, N. An overview of satellite synthetic aperture radar remote sensing in archaeology: From site detection to monitoring. *J. Cult. Herit.* **2017**, *23*, 5–11. [CrossRef]
86. Fantoni, R.; Caneve, L.; Colao, F.; Fiorani, L.; Palucci, A.; Dell'Erba, R.; Fassina, V. Laser-induced fluorescence study of medieval frescoes by Giusto de' Menabuoi. *J. Cult. Herit.* **2013**, *14*, S59–S65. [CrossRef]
87. Ngaruiya, J.; Ngigi, M. Diagnosis of wind turbine misalignment through SCADA Data. *Diagnostyka* **2017**, *18*, 17–24.
88. García-Ayllón, S. Retro-diagnosis methodology for land consumption analysis towards sustainable future scenarios: Application to a mediterranean coastal area. *J. Clean. Prod.* **2018**, *195*, 1408–1421. [CrossRef]
89. González, P.V.; Medina-Cetina, Z. Risk Assessment for Landslides Using Bayesian Networks and Remote Sensing Data. *Geo-Risk* **2017**, *2017*, 113–123. [CrossRef]
90. Balado, J.; Díaz-Vilariño, L.; Arias, P.; González-Jorge, H. Automatic classification of urban ground elements from mobile laser scanning data. *Autom. Constr.* **2018**, *86*, 226–239. [CrossRef]

91. Southern Housing Group. *Spatial Hierarchy & Unique Property Reference Number (UPRN) Procedures*; Southern Housing Group: London, UK, 2021. Available online: https://www.ordnancesurvey.co.uk/business-government/tools-support/uprn (accessed on 20 July 2022).
92. Chiabrando, F.; Nex, F.; Piatti, D.; Rinaudo, F. UAV and RPV systems for photogrammetric surveys in archaelogical areas: Two tests in the Piedmont region (Italy). *J. Archaeol. Sci.* **2011**, *38*, 697–710. [CrossRef]
93. BIMeo, "BIMeo—ARtoBuild". Available online: https://www.bimeo.fr/artobuild (accessed on 29 November 2022).
94. Heinrichs, B.E.; Yang, M. Bias and Repeatability of Measurements from 3D Scans Made Using iOS-Based Lidar. *SAE Tech. Pap.* **2021**, *2021*, 2219–2226. [CrossRef]
95. European Commission. *Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018*; EU member-states; European Commission: Brussels, Belgium, 2008; Volume L312, pp. 1–59. Available online: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:01:ES:HTML (accessed on 20 July 2022).