sustainability

Article

A Traceability Framework to Enable Circularity in the Built Environment

Saman Davari, Meisam Jaberi , Adam Yousfi and Erik Poirier *

Department of Construction Engineering, École de Technologie Supérieure, Montreal, QC H3C 1K3, Canada; saman.davari@etsmtl.ca (S.D.); meisam.jaberi.1@ens.etsmtl.ca (M.J.); adam.yousfi.1@ens.etsmtl.ca (A.Y.)
* Correspondence: erik.poirier@etsmtl.ca

Abstract: The transition towards a Circular Economy (CE) has been receiving an increasing amount of attention in the built asset industry. One of the key aspects of CE is traceability, which can enable the identification and tracking of materials, products, and their associated value throughout their entire lifecycle. However, achieving traceability has been challenging in the built asset industry due to the complex nature of construction projects and a lack of awareness about the benefits of traceability in achieving the circularity of building products and materials. Despite recent studies and efforts, a limited number of frameworks or guidelines exist to support traceability in the built asset industry. In many cases, several of the existing traceability standards, strategies, and guidelines must be identified and framed to support development and implementation of theories and models applicable within the built asset domain. This paper proposes a traceability framework consisting of five key components covering: the main purposes of traceability enabling CE principles, the role of traceability across asset lifecycle stages, the type of data needed to support traceability, the value of collaboration and coordination among industry stakeholders, and key enablers and drivers of traceability from technological and organizational perspectives. The proposed framework developed in this paper contributes to the effort aimed at framing the knowledge domain of CE through the traceability of products and materials in the built environment.

Keywords: traceability; circular economy; built asset industry; lifecycle information management; digitalization; sustainability; digital threading

Citation: Davari, S.; Jaberi, M.; Yousfi, A.; Poirier, E. A Traceability Framework to Enable Circularity in the Built Environment. *Sustainability* **2023**, *15*, 8278. https://doi.org/10.3390/su15108278

Academic Editors: Pierfrancesco De Paola, Rodney Stewart, Sherif Mostafa, Vidal Paton-Cole and Payam Rahnamayiezekavat

Received: 30 March 2023
Revised: 3 May 2023
Accepted: 16 May 2023
Published: 19 May 2023

1. Introduction

The built asset industry is a significant contributor to global waste and resource depletion. According to the World Green Building Council, the construction and demolition of buildings account for 40% of global energy consumption and 30% of global greenhouse gas emissions and are responsible for 25% of waste [1]. Transitioning to a Circular Economy (CE) presents a viable alternative that seeks to keep materials and products in use for as long as possible, thus reducing waste and promoting sustainable resource use [2]. One of the main goals of CE is to create a closed-loop system in which materials and products are used and reused as efficiently as possible, without creating waste or depleting resources [3]. This approach is often contrasted with the traditional linear model of production and consumption in which resources are extracted, transformed into products, and then disposed of, often in a way that is harmful to the environment [4,5]. As the principles of CE are becoming more prevalent in various fields of research, there are still several barriers associated with achieving circularity of built assets, including the complex supply chains involved in the distribution of products [6], the difficulty of tracking materials and products through the various stages of their lifecycle [7], and the lack of incentives or effective collaboration among industrial practitioners to promote circularity [8,9].

One critical aspect of CE is traceability, which enables the identification and tracking of materials, products, and their associated value throughout their entire lifecycle. The notation of traceability can be defined as the ability to track and trace the history, location, application, and movement of materials, products, or systems from the point of origin to the point of consumption or disposal [10,11], while providing detailed information about the transformation processes, intermediaries, and actors involved in each stage of the value chain [12]. Such abilities can provide opportunities to address current CE challenges by enabling full transparency of transformed and shared information throughout lifecycle stages, as well as supporting potential End-of-Life (EoL) options such as ability to reuse or recycle the disassembled products and materials [13]. To date, the concept of traceability and its applications are widely investigated in various domains including food industry, software engineering, manufacturing, and aerospace. In such domains, several published frameworks and models can be found describing the key characteristics and components of traceability to meet CE goals and outcomes [11,14,15].

In comparison to other domains, the literature on traceability studies is relatively limited in the built asset industry [16]. There is a poor understanding about the role of traceability in enabling circularity of building products and materials across various lifecycle stages [17]. Most of the existing studies have focused on specific aspects of traceability, such as the use of advanced information technologies (e.g., blockchain technology) to accelerate traceability processes [18], or have been limited to case studies of individual projects or companies. There is an apparent lack of integrated approaches to frame current industrial standards, guidelines, and strategies linking their relationships in real construction projects [13]. The main reasons for slow adoptions of traceability in the built asset industry can be investigated due to the fragmented nature of construction projects, very long asset lifecycles, and a high volume of stakeholders involved [17]. To address such issues, many academic publications put emphasis on the necessity to develop and implement integrated traceability frameworks to enable the circularity of products, materials, and systems in the built asset industry [13,17,19].

Therefore, the motivation behind this research is driven by the need to better understand the notation of traceability and its role in enabling circularity in the built environment. Due to the fact that CE is about all interrelations between materials, actors, products, elements, processes, and sectors [20], more research is necessary to describe various aspects of traceability and highlight its potential to enable circularity. Previous research has provided some insight into the relationship between the concept of traceability and CE principles [7,10,11], but some fundamental research questions remain unanswered, including the following:

- RQ1: What are the main traceability standards, guidelines, and strategies to enable circularity in the built asset industry?
- RQ2: How can these standards, guidelines, and strategies be structured and linked through an integrated approach for future studies and implementations?

Following these research questions, this paper aims to identify and link key components of traceability through an integrated framework. To accomplish this, a traceability reference model was adapted from the literature to articulate the main components of traceability under CE principle. Specifically, these elements were positioned with the intention of clarifying (i) the primary purpose of traceability in enabling the circularity of built assets; (ii) the specific information milestones at which assets can be traced; (iii) the significance of collaboration and coordination among stakeholders; (iv) the nature of data that should be traced and extracted; and (v) advanced technologies and drivers that promote the traceability of materials and products. To operationalize the theoretical constructs of the framework into practice, promising new technologies and digital tools facilitating traceability of building materials and products across their lifecycle stages are presented. Advanced technologies and drivers such as digital threads (DTH), materials passports (MPs), and collaborative platforms can take traceability to another level by increasing transparency and insight into the status, movement, and history of a product [18]. Combined with existing traceability guidelines and principles, this research has the potential to structure the body of knowledge pertaining to traceability studies and unlock new opportunities to achieve circularity goals in the built environment. The work set out in this paper is structured as follows: it begins with the literature review on the main topics related to CE and the concept of traceability across domains, followed by description of materials and methods used to characterize various aspects of traceability in the context of built asset industry. Finally, a traceability framework is proposed as a result of this research to articulate the key components of traceability that are essential for achieving circularity in materials and products across lifecycle stages.

2. Background

2.1. Circular Economy in the Built Environment

Waste generated from construction, renovation, and demolition (CDR) in Canada generated more than 4 million tons in 2021 [21]. To divert this significant amount of waste from landfills, the Canadian government is pushing the built asset industry towards a CE model by replacing the EoL concept with reducing, reusing, and recovering materials across construction and operational lifecycle stages [21]. While the body of literature pertaining to a circular future is rapidly growing, many scholars and industry experts have highlighted the significant challenges in transitioning to this new economic model [5,22–24]. There are several strategic and political challenges hindering this transition such as resistance from stakeholders in the industry who are accustomed to traditional linear approaches and do not see the value of the CE models [8,25] or the competitive nature of markets, which may make it difficult for organizations with narrow profit margins to justify the additional investment and effort required for circularity [26]. From a technical perspective, challenges include effective lifecycle information management to increase the circularity of materials and products within and between organizations and regulatory bodies in the built asset industry [27]. Achieving circularity depends heavily on the availability of data that is relevant, reliable, and readily accessible [28]. Without such data it is hard to track the properties of materials, products, and systems and measure their economic, social, and environmental impacts [29].

One opportunity for accessing required data is the use of materials passports (MPs) [30]. MPs are a set of digital documents containing composition data, environmental product declarations (EPDs), and provenance of building materials and products and showing their potentials for recovery and reuse [31,32]. A growing number of passport-types have been proposed by scholars and practitioners [33–35]. However, it may cause difficulties in collecting and matching incoherent data from multiple MPs [36]. Examples of MPs include the following:

- Buildings As Material Banks (BAMB): this MP describes data and their implementation strategies in the built environment. All necessary information about materials and products pertaining to CE is hierarchically categorized into several levels (Figure 1) such as material properties, certifications, logistics, etc. The project has also established a digital platform which connects individual components of the buildings by displaying their uses and values in the marketplace [31].
- 3XN Architects: this MP provides guidelines to collect CE data across a building's lifecycle stages. The collected data need to be linked to a database enabling traceability of all building components and parts with their technical and functional specifications [37].
- Madaster: this project frames MP data based on the building's layers (e.g., structure, skin, services, etc.). The MP also provides circularity indicators to calculate the amount of virgin, recycled, reused, and renewable materials that are incorporated within a building. Madaster's cloud platform can connect to Building Information Modeling (BIM)-based models and allows users to create and develop a unique passport for buildings or objects [38].

In addition to the application of MPs, transition to an advanced CE requires a high degree of digitalization and automation [39]. The main barriers that hinder this potential are primarily related to what can be described as an information gap between industrial parties [40]. This information gap appears when there is no transparent and common understanding about what, when, which, where, why, and how CE data are circulated and exchanged among the involved parties in a project. It is becoming increasingly important to close this gap by ensuring traceability of all relevant CE-related data and linking them into a structured knowledge base [41,42]. Nevertheless, disregarding digitization's upheaval influence, there are still certain issues which need to be addressed. These might include a digital gap across lifecycle phases and project stakeholders [43]. Finally, traditional project delivery practices tend to create barriers between project stakeholders which leads to a collaboration gap [44]. Figure 2 demonstrates these gaps across asset lifecycle phases. To fill these gaps, an integrated and automated solution is very much needed to link and put key components of circularity into relationship.

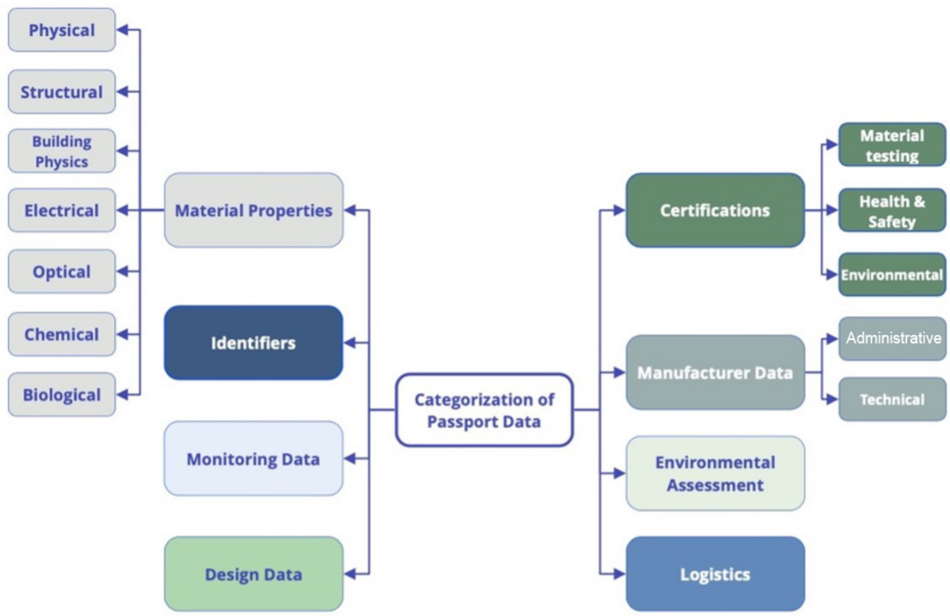

Figure 1. Categorization of MP data (adapted from BAMB [31]).

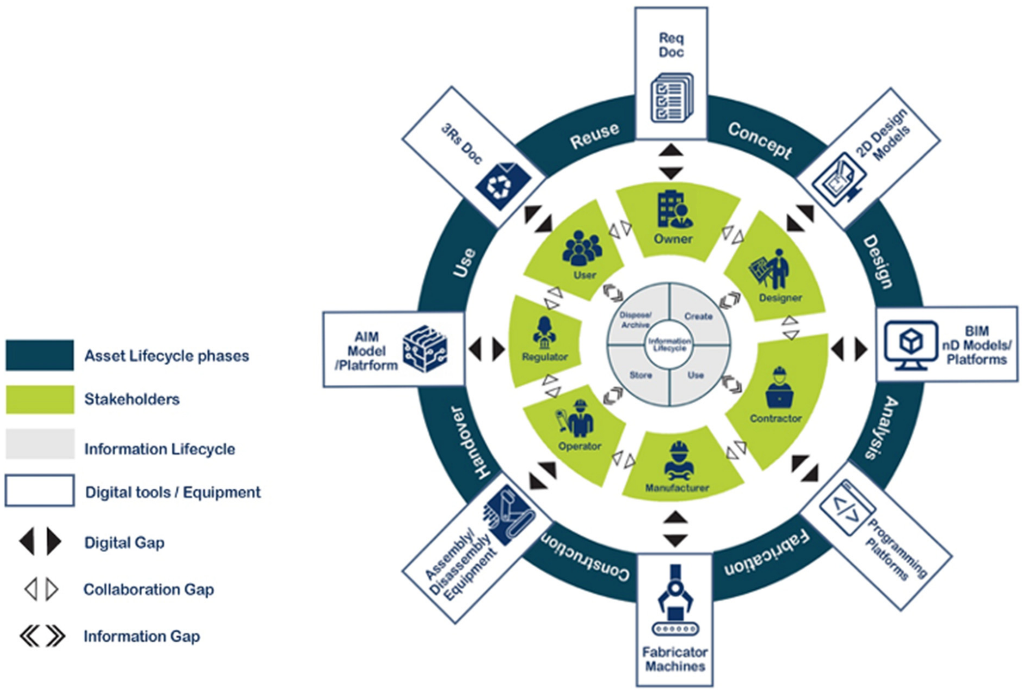

Figure 2. Overview of current gaps in asset lifecycle phases.

2.2. Concept of Traceability across Domains

Traceability of materials and products is recognized as one of the major concerns in an increasing number of CE studies and practices across various domains [45]. Although there is no definitional ambiguity that encompasses all aspects of traceability [17], the notion of "traceability" has been defined in the literature as listed in Table 1.

Table 1. Definitions of traceability.

Ref	Definition	Context	Year
[46]	"The ability to trace the history, application, or location of an entity by means of recorded identifications".	ISO8402	1994
[41]	"The ability to access any or all information relating to that which is under consideration, throughout its e tire lifecycle, by means of recorded identifications".	Food industry	2018
[47]	"Client requirements have to be presented in a manner that will facilitate: (. . .) [t]he traceability of design decisions to original requirements throughout the life cycle of the facility".	AEC [1]	2000
[48]	"Traceability involves knowing where the product or raw material comes from, real-time location throughout the supply chain, and its conditions regarding pre-set quality at each stage of the roadmap".	AEC	2021
[13]	"The ability to follow information related to a product through its supply chain" (p. 3) providing a number of uses: quality and safety, minimizing scandals that damage company reputations, improved supply chains, and enhancing trust".	AEC	2017

[1] AEC: Architecture, Engineering, and Construction.

Most academic publications stress the importance of traceability models around which the tracing processes, tools, and methods can be defined and organized [11,49–51]. Some of the most common traceability models are described in Table 2. Given models' vast range of applicability, specific use cases within specific sectors are required to fully leverage their potential.

Table 2. Traceability models.

Model	Description	Ref
Physical traceability	This model is focused on tracking and tracing physical products, such as food and manufacturing products, through the supply chain.	[52–54]
Information traceability	This model is focused on tracking and tracing the flow of information, such as data and records, within the supply chain.	[55–58]
Genetic traceability	This model is focused on tracking and tracing the genetic makeup of biological products, such as seeds, livestock, and crops.	[59–61]
Process traceability	This model is focused on tracking and tracing the processes and steps involved in the production of products, such as manufacturing processes and quality control procedures.	[62,63]
Event traceability	This model is focused on tracking and tracing specific events or activities, such as deliveries, shipments, and product recalls.	[64–66]
Systemic traceability	This model is focused on tracking and tracing the interactions and relationships between different elements within the supply chain, such as suppliers, manufacturers, distributors, and consumers.	[67,68]
Hybrid traceability	This model combines elements of different traceability models to provide a comprehensive and integrated traceability system.	[69–71]

Recent studies have emphasized the role of information traceability in mitigating quality and safety issues, optimizing resource productivity, facilitating information retrieval for management practices, and improving supply chain by increasing trust between suppliers and consumers in the context of sustainable development [14,19,48]. Organizations can also utilize information traceability to locate the sources of mistakes or discrepancies in their data and keep an accurate record of changes made over time [72,73]. In a study conducted by Moe [74], internal traceability and chain traceability were identified as two common information traceability methods. Internal traceability can be performed within a single stage of the product lifecycle, allowing for improved planning and optimization of raw material use as well as identification of causes and effects to conform to product standards. Chain traceability, on the other hand, enables the tracking of product information throughout its entire lifecycle, from early stages such as planning and conceptual design to end-of-life (EoL). This level of traceability is essential for accessing information about a product's history and ensuring compliance with regulations, standards, and quality control [75]. Data related to information tractability can be obtained from entities, processes and activities (services), project context, and stakeholders involved in a product's supply chain (e.g., suppliers' name and their responsibility) [31]. However, it is still not clear how to use such data and at which lifecycle stages data should be traced to meet circularity requirements.

Different traceability methods, models, and frameworks have been proposed in different domains to improve the tracking and flow of information for sustainability purposes. For example, Anastasiadis [76] proposed a holistic transability framework emphasizing the relationship between sustainability principles and agri-food supply chains. The proposed framework consists of several key elements, including stakeholder analysis, supply chain analysis, development stages, testing through multiple real case scenarios, and assessment stage. Based on the defined elements of this framework, it can be found that effective information exchange and collaboration among stakeholders through the use of innovative technologies such as cloud computing, big data, blockchain, and the Internet-of-Things are essential to meet consumer needs and sustainability goals in general. Such findings support an argument that any traceability approach should meet the demands of major stakeholders while having positive impacts on economic, social, environmental, and governance aspects of the sustainable development.

Katenbayeva et al. [13] integrated some of the key concepts related to traceability with respects to sustainability (Figure 3), including their relationship and breadth of application. Traceability in this approach is closely linked to transparency and responsible sourcing. At the management level, organizations use traceability as a tactic to increase the transparency in their business decisions. In addition, all operations within an organization can be actively traced to ensure responsible use of natural, financial, and human resources [77]. As an ultimate goal, the consistent integration of traceability into decision-making and practices can result in ethical growth for businesses and industries, while also promoting sustainable trade practices.

Figure 3. Key concepts related to traceability for sustainable development (adapted from Katenbayeva et al. [13]).

Each stakeholder plays a critical role in ensuring the traceability of products and processes [78]. It is important that they work closely together to ensure that the system is effective, and that accurate information is maintained throughout their lifecycle. Poor communication between stakeholders can result in gaps in information and misunderstandings that can hinder traceability. Ramesh and Jarke [79] introduced a simple "traceability reference model" emphasizing on what, who, where, how, why, and when information should be traced. Such simple questions were categorized as key dimensions that need to be addressed for ensuring the accuracy and effectiveness of traceability systems. Using these dimensions in traceability practices can increase transparency, reduce the risk of product recalls, and enhance consumer confidence in the products they purchase [79]. Similarly, Ouertani et al. [80] proposed a standardized framework and defined similar dimensions (what, who, where, how, why, and when) to support traceability of product knowledge during lifecycle stages. Using these dimensions, the authors systematically mapped traceability requirements through the lens of various stakeholders (e.g., planners, owners, regulators, etc.) and identified specific enablers, development phase, and activities that support traceability applications. Adoption of these research dimensions permits contextualization of all related concepts and strategies in the built environment.

2.3. Traceability in the Built Asset Industry

Implementation of information systems and practices enabling traceability in the built asset industry varies depending on the region, sector, and specific application. In general, the industry has been relatively slow in adopting these systems and practices compared to other industries [48]. One reason for this is the industry's notorious fragmentation [48]. The built asset industry is made up of various stakeholders that each have their own set of requirements and standards. Another reason for this slow adoption is the lack of a standardized approach. Unlike other industries, such as food or pharmaceuticals, there is no universally recognized guideline or standard for tracking and tracing building materials and components [13]. Some organizations have developed domain-specific guidelines for tracking and tracing building materials and products, such as the Building Research Establishment (BRE) in the UK [81] and the Green Construction Board's Supply Chain Sustainability School [82]. In 2014, BRE established BES 6001 requirements (Figure 4) for the responsible sourcing of construction products, which considers factors such as environmental and social impacts, ethical sourcing, and supply chain management. The standard covers a wide range of construction products, including metals, timber, aggregates, and insulation materials. Traceability is an important element of the BES 6001 standard, as it helps to ensure that the construction products being used are responsibly sourced and sustainable. BES 6001 requires construction companies to demonstrate the traceability of their products by identifying the sources of the raw materials, as well as the suppliers involved in the production and delivery of the finished products. This includes identifying any potential environmental or social risks associated with the sourcing of the materials, such as deforestation, human rights violations, or other unsustainable practices [81].

Digitalization of a traceability process is another critical aspect that should be considered by leveraging the next generation of automated tools or systems [83]. Companies can establish a comprehensive and accurate record of the origin and movement of their construction products through digital traceability technologies [16]. This includes capturing and making available data about the source of raw materials, streamlining processes, and reducing the time and effort required to collect and manage any relevant information about the product and the supply chain. Regarding current regulations, in the European Union (EU), the Construction Products Regulation (CPR) requires that construction products must be traceable through their entire supply chain, from raw materials to the finished product [84]. The CPR also requires that products be accompanied by a Declaration of Performance (DoP) that provides information on the asset's performance characteristics, such as fire resistance and mechanical strength. In the United States, the Environmental Protection Agency (EPA) requires that contractors performing renovation, repair, and painting projects that disturb lead-based paint in homes, childcare facilities, and schools built before 1978 follow specific practices to prevent lead contamination [85]. This includes maintaining records of lead-safe work practices used on each job. Additionally, some voluntary certification programs, such as Leadership in Energy and Environmental Design (LEED), encourage traceability by awarding points for using materials with recycled content, sustainable sourcing, and transparency in reporting the product's environmental and social impacts [86].

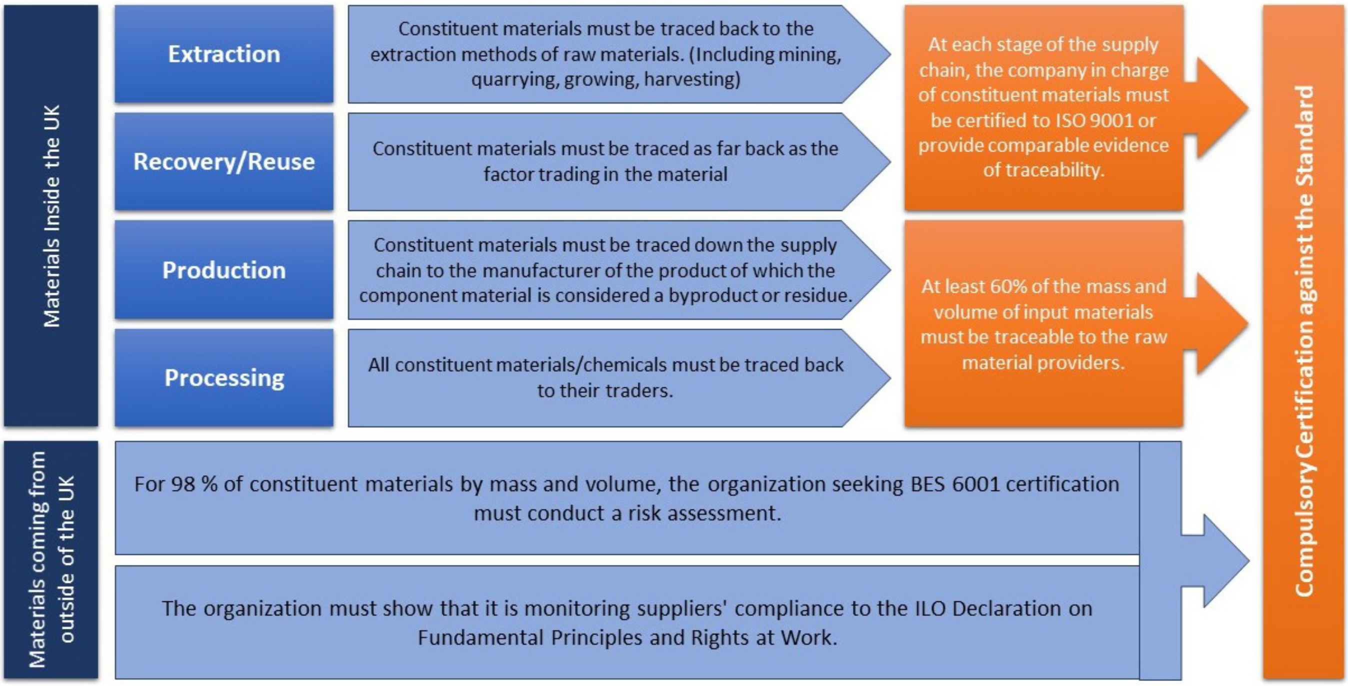

Figure 4. Traceability in the construction sector—adapted from BES 6001 standard (adapted from BRE [81]).

In accordance with the existing guidelines and strategies, Watson et al. [17] proposed a wholistic digital recording framework (Figure 5) supporting the traceability of building materials and products across their lifecycles. The framework is designed to enable an accurate and reliable record of every traceable resource unit (TRU) from requirements to in-use chains. Here, TRU can be any unit of material, component, or finished product that is assigned a unique identifier (e.g., barcode or serial number) and recorded as it moves through the various chains. This unique identifier can be used to retrieve data on the TRU's origin, processing, transportation, storage, and distribution [19]. As TRUs can be found in both physical and information chains of an asset, digital recording occurs at key points in time which are indicated as "traceable events" in Figure 5. Understanding the relationships between such traceable events is crucial as it provides stakeholders broader insight from all processes and activities throughout different chains. Most recently, the application of DTHs has provided opportunities to seamlessly link and harmonize multiple TRUs across lifecycle stages [87].

Based on the key principles of digital recording framework by Watson et al. [17], Li et al. [88] integrated BIM, IoT, and distributed ledger technology (DLT) to enhance traceability of digital data recorded from initial design phase to the maintenance and operation (M&O) phase of an asset. This integration of technologies and systems automates transfer of data between stakeholders and linking of relevant information that are digitally recorded across an asset's lifecycle. Having the linked data available can significantly accelerate a traceability process and improve management and operational effectiveness. There are currently many advanced technologies enabling data linking for traceability purposes such as application of blockchain technology [89] or digital threading of critical lifecycle information needed to trace physical/digital built assets [90]. However, integrating such technologies under CE principles and implementing them for domain-specific traceability scenarios requires the development of an integrated framework which is currently missing in the literature.

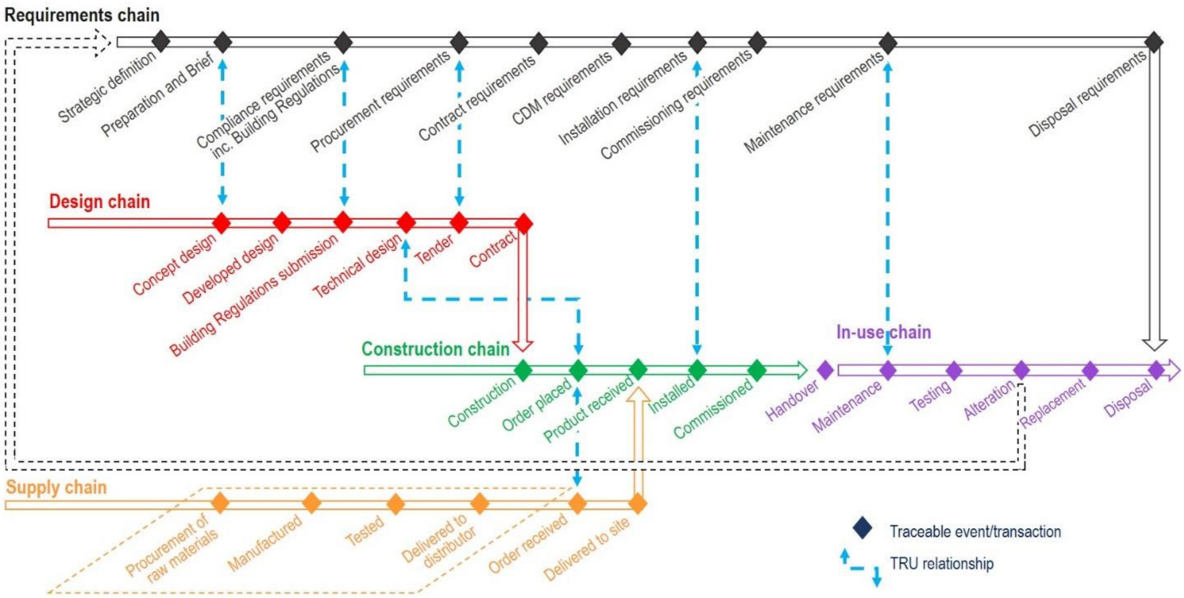

Figure 5. Framework for digital recording in construction (taken from Watson et al. [17]).

Overall, improving traceability in the built asset industry requires a multi-faceted approach that involves various stakeholders throughout the requirements, design, construction, supply, and in-use chains. Many scholars and industrial experts have agreed on certain necessary actions such as establishment of clear standards and guidelines [13], adoption of innovative digital technologies (e.g., blockchain systems) [48], encouraging collaboration and communication among project parties [19], regular monitoring and verification of supply chain performance [51], etc. However, there is still a lack of comprehensive understanding of such actions in relation to CE requirements in the built asset industry.

2.4. Summary of Research Gaps

Despite the increasing interest in traceability of materials and products throughout built asset lifecycle stages, there is a notable lack of research and understanding around its framing, application and integration into existing standards, strategies, and guidelines to support implementation [13]. Stantana and Ribeiro [11] conducted a comprehensive literature review to map the existing traceability models and frameworks across domains. The authors of this study listed a few traceability models in the construction sector with a focus on effectiveness of technological systems (e.g., RFID system, GPS tags, blockchain technology) for tracking the building fabrication process or construction site logistics [91,92]. To date, only a few studies have highlighted other aspects of traceability in the built asset industry and discussed the actions needed to enable circularity of building materials and products across lifecycle stages [13,14]. This includes poor understanding of the main types of data enabling traceability, lifecycle stages where data can be potentially traced, key technologies to facilitate traceability in data management and documentation, and the relationship among stakeholders involved in the traceability process. These gaps in the literature are significant, as they prevent a complete understanding of the concept of traceability through the lens of CE. Current research often emphasizes single aspects of traceability, such as documentation management or change control, rather than examining the broader impact of traceability on the circularity of products and materials. Therefore, there is a need for further research to investigate the relationship between different aspects of traceability and their potential to support CE principles in the built asset industry.

Such research can provide valuable insights for industry practitioners and policymakers, deriving progress towards a more sustainable and circular built environment.

3. Materials and Methods

The principal objective of this research is to develop a material and product information traceability framework for the built asset industry and to pilot its application to pursue principles of CE. To achieve this objective, the concept of traceability and its role in enabling a circular economy has been defined, developed, and framed through a series of research activities and workshops with industry experts. These activities are explained in the following sections.

3.1. Adoption of a Traceability Reference Model

Based on the traceability reference model proposed by Ramesh and Jarke [79], the framework is expected to explain all relevant dimensions of traceability including the following:

- Why are we tracing: refers to the purposes and drivers of traceability to all stakeholders. The framework should cover specific needs and goals of stakeholders and provide a rationale for why traceability is necessary in each case. Some possible drivers for traceability include improving quality control, ensuring compliance with regulatory requirements, increasing transparency and accountability, supporting sustainability and environmental goals, and reducing risk and liability in specifying, procuring, installing, and reusing or recycling products and materials.
- What are we tracing: refers to the materials, products, or systems that require traceability and the data elements that need to be traced for each item. Determining what needs to be traced can be influenced by various factors, such as regulatory requirements, project-specific requirements, and stakeholder needs.
- How are we tracing: refers to the strategies and enablers that are used to trace and manage data and how stakeholders are involved in the process. The framework should provide guidance on how data are captured, managed, and shared and how stakeholders can access and use the data.
- Who is tracing: refers to the stakeholders responsible for implementing and maintaining traceability and how they can contribute to and benefit from the traceability efforts. This includes various stakeholders involved in the built asset industry, such as designers, manufacturers, suppliers, contractors, and owners. The framework should also provide guidance on the roles and responsibilities of each stakeholder in the traceability process.
- When are we tracing: refers to the specific stages or chains of the asset's lifecycle when traceability is necessary, as well as any time constraints or deadlines that may apply. For example, traceability may be necessary during the design and planning stage to ensure that the specified materials and components meet the required specifications and standards. It may also be necessary during the construction stage to ensure that the specified materials and components are actually installed in the building, and that they meet the required quality standards.

3.2. Developing the Traceability Framework

Addressing each dimension of the traceability reference model requires a thoughtful articulation of the existing standards, guidelines, principles, enablers, and strategies into a logical framework. For this purpose, we took four steps to define the main components of the traceability framework. Accordingly, a series of four workshops were organized to involve the solution team and the industrial experts for evaluating the reviewed literature, future outcomes, application of the traceability framework, and identification of use cases and their values in the built asset industry. The selection of industry experts was carried out based on their professional background, interest, education level, and participation within the partner organization of the Center for Intersectoral Studies and Research on the Circular Economy (CERIEC). Table 3 summarizes the participants' profiles and their demographic information in subject matter.

Table 3. Industry expert profile.

Participant ID	Professional Background	Interest	Educational Level
1	Project manager	Environmental management—sustainable development.	Master's
2	Project consultant	Construction materials—sustainable development—energy efficiency.	Diploma
3	Senior director and consultant	Technology research (chemistry and materials) and sustainable innovation.	Ph.D.
4	Professor	Construction materials—lifecycle assessment.	Ph.D.
5	Project director	Traceability systems for contaminated soils.	Bachelor's
6	Marketing director	Traceability and transparency along the supply chain—traceability solutions for natural resources and environment.	Bachelor's
7	Engineer	Evaluation of carbon reduction and circular economy strategies—life cycle assessment and circularity concepts.	Bachelor's
8	Project consultant	CRD waste management—sustainable development	Master's
9	Construction consultant	Sustainability metrics—sustainable business development	Master's
10	BIM specialist	BIM—information requirement management research/improvement initiatives	Master's
11	Architectural designer	BIM management—raw and residual materials—traceability solutions	Diploma

To begin with, the concept of traceability in the built asset industry had to be framed, along with its obstacles, developments, and prospects as outlined in the literature. This involved searching academic publications, industrial reports (e.g., Arup, BAMP), books, and other sources related to the research objectives. Over 200 publications in the fields of CE and traceability were narrowed down based on their relevance to the subject matter and number of citations. The initial content analysis was conducted to identify key concepts such as principles of information traceability, barriers and potentials of CE, traceability strategies and techniques in the context of built asset industry, etc. Each item was broken down into small and manageable categories that could be scrutinized separately. All specific characteristics and qualities of traceability were examined precisely, as well as their instances and applications in different domains. Next, the initial workshop, which aimed to introduce the participants to the latest advancements and gather their thoughts on why traceability is crucial in this domain was conducted. Additional feedback on the applicability of the traceability framework and its potential to bridge the existing research gaps were collected. The second step served to synthesize the findings from the literature review and the first workshop. This involved identifying common themes, patterns, and commonalities across data sources, including (i) standards and guidelines from organizations such as ISO, IEC, and CEN; (ii) guidelines and best practices from industry associations and government agencies such as BAMP and BRE; and (iii) case studies and examples of traceability initiatives in the industry. During the second workshop, industrial experts critically evaluated the summary of findings and suggested areas for future research. In the third step, all meaningful principles, strategies, drivers, and enablers were grouped and linked to the traceability reference model in order to formalize the key components of traceability framework. The defined dimensions of the work by Ramesh and Jarke [79] were used to assess whether any themes are related, different, or overlapping. In this process, each traceability component was critically analyzed in relation to its detailed elements. After multiple revisions of the proposed framework, the third round of workshops was held with participants from lab construction and other industrial experts from various disciplines. Based on the results of the third workshop, various avenues were discussed to identify the link between traceability components and CE, evaluation of data that are needed to enable traceability across lifecycle stages, and how traceability framework can enable CE through its defined components.

In the last step, the final and revised version of traceability framework was presented to construction lab and industrial experts involved in the research project. The outcome of this step was identification of potential applications and use cases of the framework for future research. The framework development process, including workshops, is summarized in Figure 6.

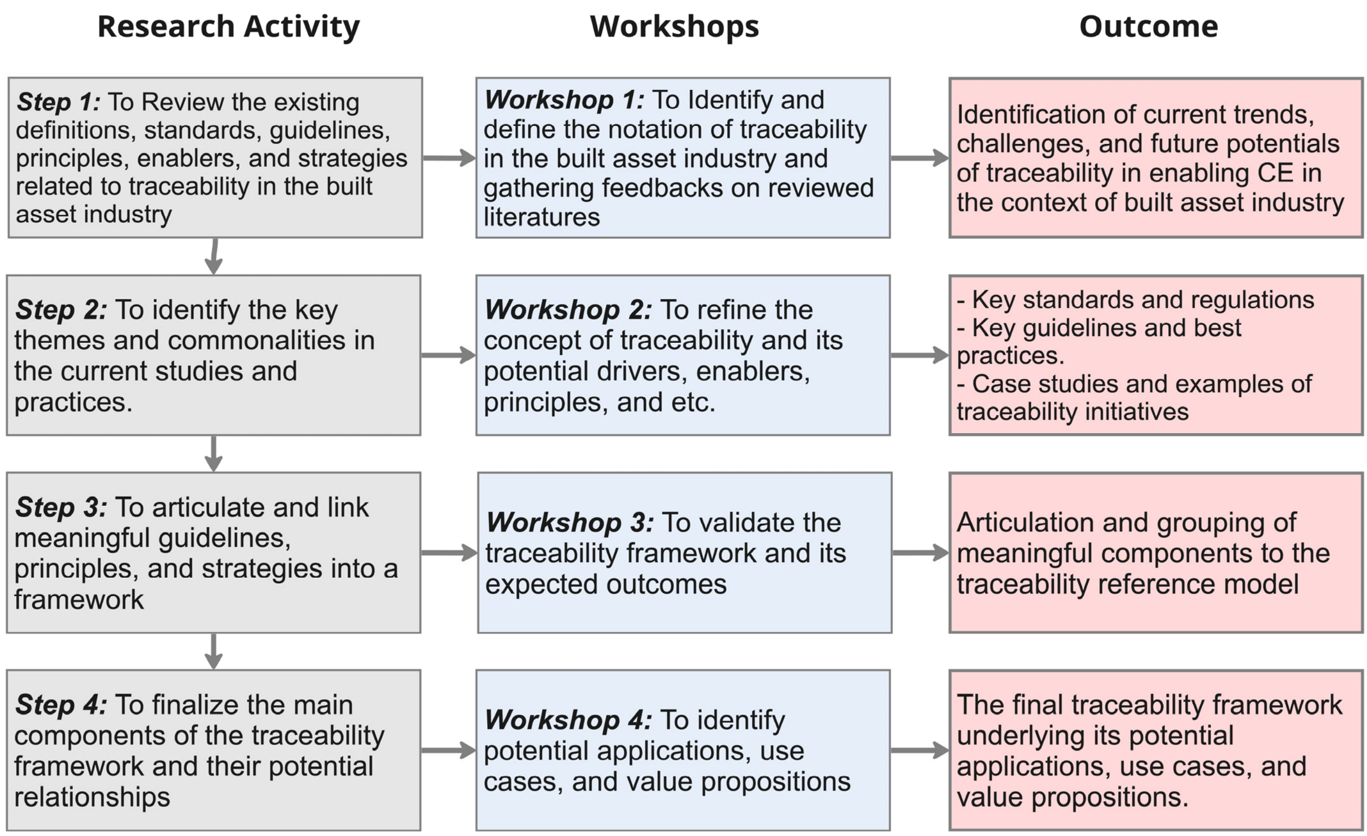

Figure 6. Summary of key research activities and conducted workshops to formalize the traceability framework.

4. A Traceability Framework for the Built Asset Industry

The overarching outcome of this research is a traceability framework that articulates the different components defining traceability and its facilitating factors to improve the circularity of the built asset industry. This section presents the traceability framework by bridging the key findings from the literature and workshops to the traceability reference model by Ramesh and Jarke [79].

While the traceability reference model can be applied to various domains, it is important to understand how it relates to the context of the built asset industry and what principles, drivers, enablers, and strategies need to be considered to facilitate circularity across an asset's lifecycle stages. The result of this contextualization is defined through the traceability framework as shown in Figure 7. In the following sub-sections, each component of the framework is described.

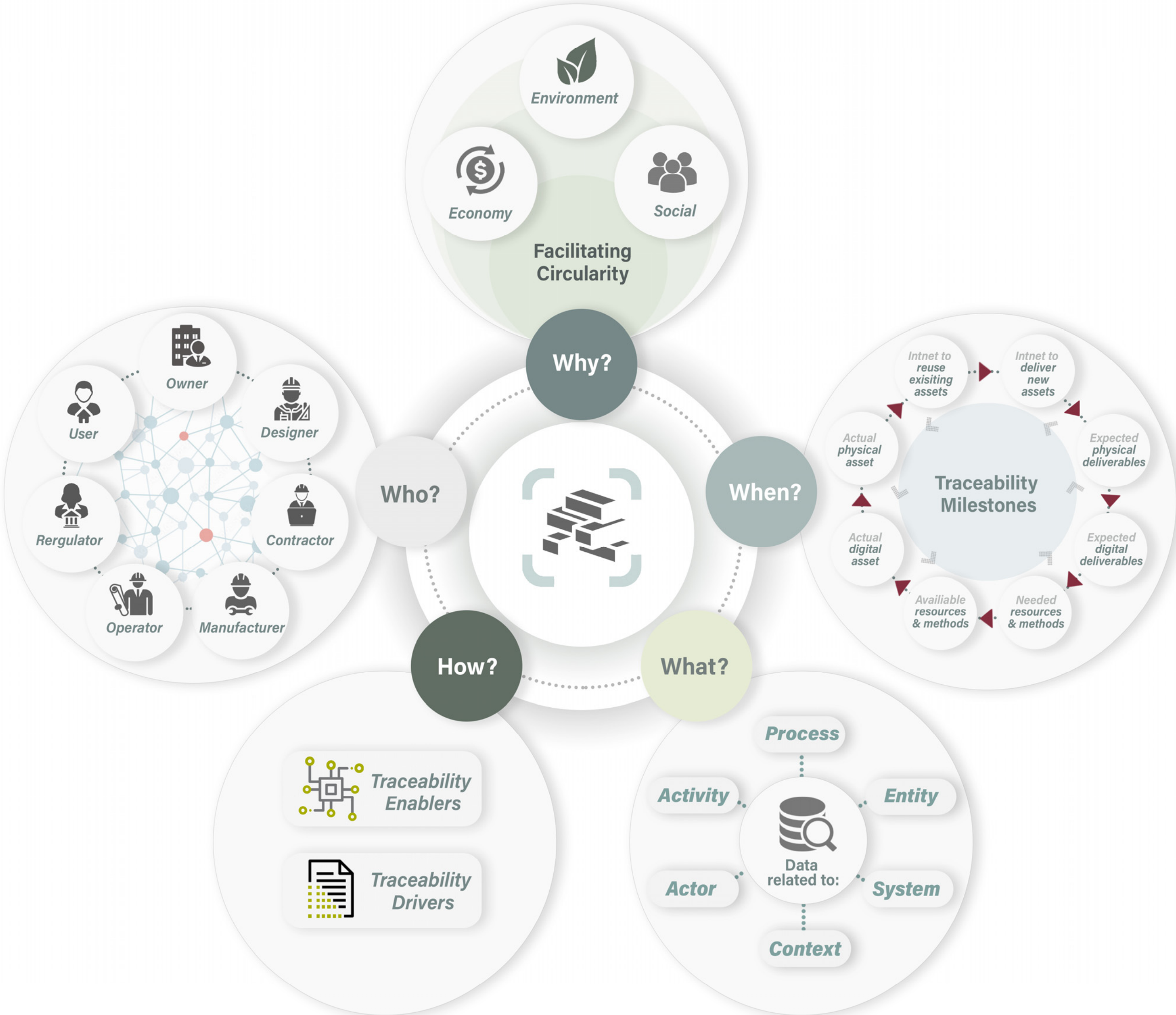

Figure 7. The traceability framework for the built asset industry.

4.1. Why: The Importance of the Sustainable Development

With the increasing application of CE models as a sustainable substitute for the conventional linear economy, the significance of traceability in the built asset industry is expected to rise [25]. One of the common purposes to apply traceability is tracking and recording the movement of materials and products throughout the asset's lifecycle stages [13]. However, the purpose of traceability should go far beyond the management of building products and resources. Most often, leading companies may find it difficult to design a building with the end in mind. In other words, architects and designers may plan the buildings without a view that they will be disassembled or deconstructed for future reuse or recycling. In such circumstances, an effective traceability system can capture accurate and reliable information about the origin, composition, and impact of products and materials throughout the asset's lifecycle. Once data has been collected and structured, it becomes easier to address circular options by tracing and optimizing the second life of products and materials under CE principles. According to Durmiševic et al. [93], inadequate reuse and recovery of materials and products is frequently caused by a lack of information on the current composition of built assets, as well as their actual location, condition, and history. Traceability allows stakeholders to obtain a comprehensive insight from the past, current, and future status of built assets, promoting smarter use of products and materials and extending their lifespan. As the result, stakeholders may find it easier to decide which 9R-strategies, as listed in Figure 8, are optimal and aligned with project context and goals [94]. Overall, sustainable development can be regarded as an ultimate goal to apply traceability in the built asset industry. Therefore, the purpose of any traceability system should directly or indirectly address environmental, financial, and human concerns under sustainability principles.

Smarter product use and manufacture	**R0**	**Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	**Rethink**	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	**Reduce**	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	**R3**	**Reuse**	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	**Repair**	Repair and maintenance of defective product so it can be used with its original function
	R5	**Refurbish**	Restore an old product and bring it up to date
	R6	**Remanufacture**	Use parts of discarded product in a new product with the same function
	R7	**Repurpose**	Use discarded products or its part in a new product with a different function
Useful application of materials	**R8**	**Recycle**	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	**Recovery**	Incineration of material with energy recovery

Figure 8. R-strategies in CE (adapted from Morseletto [94]).

4.2. What: The Main Data Types Enabling Traceability

When considering the use of traceability across an asset's lifecycle stages, stakeholders significantly rely on data to make effective decisions about the performance or quality of their products, services, and processes [27]. The review of MPs showed that actors or machines involved in traceability must be able to recognize and extract the correct type of data [31]. Different types of data have different characteristics and require different methods for handling and analysis. Indeed, determining the suitable algorithms or methods to analyze the data can be a difficult task if the required data type is unknown. Based on the previous studies presented in Section 2.1, data that enable traceability can be categorized into six types: (i) entity; (ii) process; (iii) activity; (iv) system; (v) context; and (vi) actor. Entities, such as products, components, or materials, are typically included within the system to track their movement and location and to ensure that they meet their defined requirements. Processes and activities are traced to identify the steps involved in the production or delivery of a product and to ensure that each step is completed correctly. Systems may also be traced to identify the dependencies between their constituent parts and to ensure that changes to one part of the system do not have unintended consequences for other parts. Actor data refers to information about the individuals, organizations, or their relationships that are involved in the provisioning or delivery of projects, handling, or use of the product or entity being traced. This can include information related to the identity of the actors, their roles and responsibilities, and their interactions with other actors or with the system, entity, and processes. Lastly, context data can enable a traceability system to provide valuable insights into the external factors that impact the performance and quality of the system. For instance, tracing contextual data about user demand can help to identify areas where materials and products should be optimized, or tracing regulatory compliance data can help to ensure that the asset is meeting all relevant standards and requirements. In addition to these main data elements, other data that may be traced in a traceability system could include requirements, specifications, test results, and audit records.

4.3. When: The Role of Traceability across Lifecycle Stages

Traceability plays a crucial role in every stage of the asset's lifecycle, from intent to deliver new asset to intent to reuse existing asset. According to Succar and Poirier [95], there are eight milestones for information that can be transformed and exchanged across an asset's lifecycle. The term "information milestone" is a marker along the path that information travels along an asset's lifecycle [96]. In fact, it allows practitioners to trace information through the following milestones: (1) intent to deliver new asset; (2) expected physical deliverables; (3) targeted digital deliverables; (4) needed resources and methods; (5) available resources and methods; (6) actual digital assets; (7) actual physical asset; and (8) intent to reuse existing asset. Of interest in the context of this paper, information can be traced from the initial understanding of what the primary intent is to trace an asset to its potential R-strategies (e.g., reuse, recycling, refurbishment, etc.) that can be explicitly decided at the eighth milestone. BRE [81] and stressed on the role of the traceability at EoL of an asset by providing the record of the asset's history, components, and its functional and technical condition. Such information is essential for making informed decisions about the most appropriate reusability and recycling strategies for the products and materials [30] and for ensuring that the process is carried out in a circular and responsible way.

There are several ways to ensure traceability across lifecycle stages. According to Pinheiro [51], products and materials can be traced either forward or backward. Forward traceability is the ability to trace the flow of materials and products forward in time, from the requirement phase to the end use of the built asset. This helps to investigate the impact of changes and to ensure that the materials and products used in the construction of the asset meet the desired quality, safety, and environmental standards. Backward traceability, on the other hand, involves tracking the flow of materials and products backward in time, from the end use of the built asset to its origin and initial requirements. Tracing backward allows users to reveal all historical information associated with a product or material. This becomes particularly useful in the case of renovation and refurbishment projects when all digital records may be used to support decisions on the reusability or recycling of the existing materials and products.

4.4. Who: Effective Collaboration and Coordination

The successful implementation of traceability relies significantly on close collaboration and coordination among project teams [44,97]. Lack of coordination, which results from an inability to share data and knowledge between actors, unclear ownership of specific activities supporting traceability, the absence of standardized collaboration processes, and the resistance to change from development teams, have been reported as the most common barriers to effectively implement of traceability solutions in the built asset industry [48,95,98]. Understanding the relationships between traceability actors is critical as it increases the transparency, trust, and accountability in lifecycle phases and enables the identification and resolution of CE issues [15,99]. In practice, information enabling circularity can be traced and used by strategic traceability users and operational traceability users [51,79]. In general, strategic traceability users are interested in managerial issues such as a facility manager determining what information must be traced and by whom or a regulator looking for compliance with all applicable regulations related to circularity, including waste management regulations, EPR (extended producer responsibility) requirements, and recycling standards. Operational traceability users are more interested in technical issues within a traceability system, process, or activity—for example, a coordinator who documents transformation of requirements to design and simulation or a manufacturer who decomposes design properties of a component for fabrication purposes.

There are several ways to encourage traceability actors for active collaboration and coordination, such as the following:

- Shared vision and objectives: develop a shared vision and set of objectives for the traceability project that align with the CE goals of all stakeholders involved [100].
- Communication and information sharing: foster open and effective communication channels and process knowledge management between stakeholders and share relevant information about the traceability project and its progress [98].
- Incentives and benefits: identify and communicate the incentives and benefits that arise from the successful implementation of traceability, such as improved efficiency, cost savings, and enhanced reputation for all project members [101].
- Capacity building and training: provide capacity building and training opportunities to cycle actors to enhance their knowledge and skills related to traceability and CE [45,101].
- Standardization and certification: promote the adoption of standardization and certification schemes for traceability systems to increase the trust and acceptance of the technology among stakeholders [102,103].
- Continuous improvement and evaluation: continuously evaluate the traceability system and its impact on CE goals and use the feedback to improve the system and increase stakeholder buy-in [104].

While such examples may contribute to close the collaboration gaps among traceability actors, the importance of traceability should also be actively promoted and taught. This results in appropriate traceability awareness among project actors and enhances them to make effective decisions at various circumstances.

4.5. How: Traceability Enablers and Drivers

If companies decide to implement traceability practices, they have to come up with effective drivers and enablers to support any traceability process or activity [19]. Understanding how information should be traced and linked to multiple components of a traceability system is crucial before any implementation. As mentioned, an extensive number of publications emphasized the role of material passports to enable circularity through traceability systems [30,36,105]. MPs particularly categorize traceable information (as shown in Figure 1) related to properties of building materials and guide traceability actors to which data need to be traced through RFID tags, barcodes, unique identifiers, etc. [31]. To better integrate multiple passports data, a material passport platform (MPP) has been recently introduced by BAMB [36], enabling project parties to share and customize their products' data based on MP guidelines. Such a platform and its database can be used by actors to obtain a transparent digital record of materials, as well as a diverse set of insights from various disciplines. In addition, the use of product data templates (PDTs) describes the detailed properties of products in a way that can be traced to a credible source. PDTs can also help to ensure the quality and safety of products by providing information about their designing and manufacturing processes. Such information can be used to identify potential hazards and risks associated with a product, as well as to monitor compliance with relevant regulations and standards [106]. PDTs become product template sheets (PDSs) when they are used as a basis for creating a specific product template for a particular product [107]. By using a PDS, designers and engineers can ensure that all necessary information about a product is included, such as its dimensions, weight, materials, manufacturing processes, and other relevant data. Both PDTs and PDSs serve traceability as a common framework to manage most up-to-date data and provide transparent and credible data sources.

An appropriate use of information sources is another important aspect that should be well-planned at early phases of any traceability project. BIM plays a crucial role to accumulate lifecycle information of buildings into a shared and collaborative manner [108]. The integration of MPs in BIM environment provides opportunities to document materials compositions, represent materials and products embedded in the built assets, and show various design combinations for reusing or recycling potentials [32]. Using a BIM-based MP provides traceability actors a centralized database consisting of all relevant data described in Section 4.2.

To overcome possible interoperability issues, openBIM is a collaborative approach that promotes seamless exchange of information among stakeholders regardless of what software and systems they use [109]. At its core, openBIM can contribute to the traceability of products and materials by enabling better communication, data sharing, increased transparency, and collaboration between stakeholders involved in a traceability practice.

Outside of the BIM environment, information may need to be transformed and exchanged across multiple disciplines to deliver an asset to its end users. Traceability becomes a daunting task in such circumstances where certain disciplines may face interpretability issues [110]. For example, design teams typically opt for BIM-based software to plan or model a specific asset. However, manufacturers may not have the same familiarity with BIM and would prefer to use domain-specific software for the fabrication process. One of the promising solutions to overcome this issue, thereby closing the information gap and the collaboration gap, is the concept of Digital Threads (DTHs) [111]. The concept of DTH has recently received attention by industry and academia as a data-driven approach supported through integrated technologies particularly for Product Lifecycle Management (PLM) and additive manufacturing [112]. Characterizing DTH under CE principles can help overcome various traceability barriers and challenges associated with transparency in supply chain, real-time data capturing, process visibility (e.g., logistic, transportation), decision making under uncertainty, and optimization of processes and products across lifecycle phases [113]. Additionally, DTH can be deployed to facilitate circularity principles, as characterized through MPs, which include material data requirements, balancing industrial input and output, process chain analysis, resource management, etc. [30].

Application of DTH in linking traceable information across lifecycle stages provides an avenue to ensure the accuracy, completeness, and integrity of data related to product development, manufacturing, and use. By enabling data capture, integration, and analysis across the entire asset lifecycle, DTH provide organizations with a comprehensive view of their products and help to identify areas for improvement and support better decision-making. Moreover, DTH is capable of linking and harmonizing multiple data inputs stored at decentralized databases or blockchain platforms into material and product traceability systems. By driving data and information along the DTH, traceability actors would not need to remember all links that were made to information and could follow a chain of links that goes beyond the initial point of a traceability process [51]. Although the benefits of DTH are becoming evident, there are still difficulties in properly aggregating a large volume of dispersed data generated by multiple users and transforming them into a unified or standardized format [87]. Such data processing and interoperability issues must be further investigated to take full potential of DTH for traceability purposes. While different solutions have been developed to enable parts of the DTH principle, namely openBIM principles and PDTs, more work is needed to push their development and adoption.

5. Discussion

Adoption of general traceability dimensions recommended by Ramesh and Jarke [79] revealed that the main purpose of traceability should not be limited to tracking the recorded information at planning, design, and construction stages but also using it to support 9R-strategies of CE. Tracing of key data will enable stakeholders to optimize EoL decisions of built products and materials with circularity in mind. In order to accomplish this purpose, practitioners should be acquainted with (1) various data types that should be correctly selected and used; (2) information milestones of the built assets; (3) effective strategies and mechanisms to close the collaboration and coordination gaps among parties; (4) integrated technologies and guidelines to facilitate data processing and sharing.

To successfully operationalize traceability in a CE perspective, companies and individuals need a clear vision about the product or material's path from raw materials to deconstructed entities. Once critical information milestones of a traceability scheme are identified and all the meaningful data is extracted, it is important to have robust and reliable enablers and drivers in place for tracing and verifying lifecycle information, thereby closing the information gap. From an organizational point of view, using MPs and PDTs can derive common ground for actors to ensure that they all have access to the same information about materials and their detailed properties. Despite these contributions, quality of data inputs, data credibility, data accuracy, and data collection have remained key challenges that must be addressed to overcome the "garbage in, garbage out" issue in MPs [30].

From a technological standpoint, the built asset industry is undergoing a digital transformation, and implementation of information technologies for traceability purposes requires adequate infrastructures, comprehensive standards, and technical expertise. Although several BIM-based approaches have been proposed in the context of CE [108,114,115], some barriers still exist such as interoperability issues [110], size and scales of the projects [4], and general resistance for data sharing [116], among others. Applications of open-access platforms and DTH principles can significantly contribute to overcome such barriers and ultimately close the digital gaps among systems and machines.

Closing the collaboration gap among actors was identified as another critical factor that should be encouraged through transparent collaboration and coordination. While several individuals and teams may be involved in a project and over the lifecycle of an asset, the establishment of a collaboration platform can facilitate communication and knowledge sharing for traceability purposes. However, encouraging all project parties to use an integrated approach to traceability would be challenging due to poor change management or unwillingness to overcome technical and financial barriers. Therefore, effective strategies should be adopted to communicate the potential benefits and incentives, increase awareness on the importance of traceability, or engage in small pilot projects to demonstrate the value of collaboration in support of traceability across lifecycle stages.

All of the identified traceability components discussed in Section 4 are theoretical implications that are associated with existing CE principles. However, there are some limitations in this study. The first limitation concerns the material choices of this research that were constrained by limited number of theoretical foundations particularity in the context of the built asset industry. It is possible that there are other traceability reference models or frameworks in different domains that were overlooked while doing this research. Moreover, the generalizability of the results is limited by collected feedback from industry experts who participated in the workshops. Therefore, some data biases may exist due to the appropriate type or professional scope of participants. Last but not least, it is necessary to validate the reliability and effectiveness of the traceability components proposed in the research by testing them in practical use cases.

Despite the mentioned limitations, the findings of this paper contribute to a clearer understanding of the concept of traceability in the built asset industry. If companies are to effectively transition from a linear economy to a circular one, the consideration of traceability components presented in this research could serve as the catalyst for implementing traceability with a holistic approach mindset. As such, in light of the many challenges discussed, individuals committed to CE and sustainable practices will recognize the opportunities that traceability can provide in terms of material and product circularity.

6. Conclusions and Future Research

This paper emphasized the significance of traceability in the built asset industry as a response to mounting circularity concerns. Although various standards, guidelines, and strategies exist in the literature to facilitate the traceability of materials and products throughout their lifecycle stages, there was still a need to integrate and frame such findings with respect to CE principles. Based on the traceability reference model by Ramesh and Jarke [79], a traceability framework was proposed including five main components to integrate: (i) the main purpose of traceability in the built asset industry; (ii) the role of traceability across lifecycle stages; (iii) the data required to support traceability; (iv) the techniques and approaches that promote collaboration among the traceability actors; and (vi) potential traceability enablers and drivers from both technological and organizational standpoints. These components of the presented framework can be used to achieve CE goals by enabling smarter use of products and materials and extending their lifespan. The research aimed at achieving this purpose by showcasing the latest advancements in traceability methods (e.g., digital recording), digital information technologies (e.g., DTHs, BIM-based approaches), and collaborative platforms (MPPs, openBIM). Leveraging such new methods and strategies may enable stakeholders to increase the circularity of all entities, activities, and processes within their companies. Since the built asset industry lacks a common framework that brings together various aspects of traceability in a holistic way, the findings of this research can contribute with an integrated traceability framework that could be used as a foundation for measuring building circularity in the future.

As such, the next steps are to continue to develop the traceability framework by overpassing its limitations that influence credibility and reliability of components and elements. This encompasses testing the proposed traceability framework with a wider group of industry professionals, gathering up-to-date information from the various parties and sources involved in a traceability process, and implementing actual use cases to demonstrate the framework's effectiveness in addressing issues related to circularity. A follow-up paper will be communicated in the future to present the specific use cases of this study and report the results of the testing and validation of the proposed framework. The potential use cases will be used to determine the applicability of the research implications in real-world situations, as well as calculation of product and material circularities using the potential CE indices and a BIM-based approach for information management of the built assets.

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

Funding: This research was funded by the construction circular economy living lab of the Center for Intersectoral Studies and Research on the Circular Economy (CERIEC) of the École de technologie supérieure (ÉTS)—the lab is supported by Desjardins Group and the government of Quebec.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: The research team would like to thank participants in Lab construction 8A: upstream traceability of materials and products coordinated by the CERIEC.

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

References

1. Laski, J.; Burrows, V. From Thousands to Billions: Coordinated Action Towards 100% Net Zero Carbon Buildings by 2050. 2017. Available online: https://apo.org.au/node/118366 (accessed on 13 March 2023).
2. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [CrossRef]
3. MahmoumGonbadi, A.; Genovese, A.; Sgalambro, A. Closed-loop supply chain design for the transition towards a circular economy: A systematic literature review of methods, applications and current gaps. *J. Clean. Prod.* **2021**, *323*, 129101. [CrossRef]
4. Grafström, J.; Aasma, S. Breaking circular economy barriers. *J. Clean. Prod.* **2021**, *292*, 126002. [CrossRef]
5. Charef, R.; Ganjian, E.; Emmitt, S. Socio-economic and environmental barriers for a holistic asset lifecycle approach to achieve circular economy: A pattern-matching method. *Technol. Forecast. Soc. Chang.* **2021**, *170*, 120798. [CrossRef]
6. Kumar, M.; Raut, R.D.; Jagtap, S.; Choubey, V.K. Circular economy adoption challenges in the food supply chain for sustainable development. *Bus. Strateg. Environ.* **2022**, bse.3191. [CrossRef]
7. Mousavi, A.; Sarhadi, M.; Lenk, A.; Fawcett, S. Tracking and traceability in the meat processing industry: A solution. *Br. Food J.* **2002**, *104*, 7–19. [CrossRef]
8. Jaeger, B.; Upadhyay, A. Understanding barriers to circular economy: Cases from the manufacturing industry. *J. Enterp. Inf. Manag.* **2020**, *33*, 729–745. [CrossRef]

9. Fischer, A.; Pascucci, S. Institutional incentives in circular economy transition: The case of material use in the Dutch textile industry. *J. Clean. Prod.* **2017**, *155*, 17–32. [CrossRef]
10. Giovanardi, M.; Konstantinou, T.; Pollo, R.; Klein, T. Internet of Things for building façade traceability: A theoretical framework to enable circular economy through life-cycle information flows. *J. Clean. Prod.* **2023**, *382*, 135261. [CrossRef]
11. Santana, S.; Ribeiro, A. Traceability Models and Traceability Systems to Accelerate the Transition to a Circular Economy: A Systematic Review. *Sustainability* **2022**, *14*, 5469. [CrossRef]
12. Corallo, A.; Latino, M.E.; Menegoli, M.; Pontrandolfo, P. A systematic literature review to explore traceability and lifecycle relationship. *Int. J. Prod. Res.* **2020**, *58*, 4789–4807. [CrossRef]
13. Katenbayeva, A.; Jacqui, G.; Anvuur, A.; Ghumra, S. Developing a Theoretical Framework of Traceability for Sustainability in the Construction Sector. 2017. Available online: https://hdl.handle.net/2134/23842 (accessed on 13 March 2023).
14. Trautman, D.; Goddard, E.; Nilsson, T. Traceability—A Literature Review. Available online: https://era.library.ualberta.ca/items/921e1026-7e1a-4add-a631-5114d6a2171f (accessed on 13 March 2023).
15. Garcia-Torres, S.; Albareda, L.; Rey-Garcia, M.; Seuring, S. Traceability for sustainability—Literature review and conceptual framework. *Supply Chain Manag. Int. J.* **2019**, *24*, 85–106. [CrossRef]
16. Hackitt, D.J. Building a Safer Future. 2018. Available online: https://www.longworth-uk.com/wp-content/uploads/2018/07/Building-a-Safer-Future-Overview.pdf (accessed on 20 January 2023).
17. Watson, R.; Kassem, M.; Li, J. Traceability for Built Assets: Proposed Framework for a Digital Record. In Proceedings of the Creative Construction Conference 2019, Budapest, Hungary, 29 June–2 July 2019; Budapest University of Technology and Economics: Budapest, Hungary, 2019; pp. 496–501.
18. Voorter, J.; Koolen, C. The Traceability of Construction and Demolition Waste in Flanders via Blockchain Technology: A Match Made in Heaven? *J. Eur. Environ. Plan. Law* **2021**, *18*, 347–369. [CrossRef]
19. Falleri, J.-R.; Huchard, M.; Nebut, C. Towards a traceability framework for model transformations in Kermeta. In *ECMDA-TW'06: ECMDA Traceability Workshop*; Sintef ICT: Trondheim, Norway, 2006.
20. Verberne, J. *Building Circularity Indicators: An Approach for Measuring Circularity of a Building*; Eindhoven University of Technology: Eindhoven, The Netherlands, 2016.
21. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
22. Michelini, G.; Moraes, R.N.; Cunha, R.N.; Costa, J.M.H.; Ometto, A.R. From Linear to Circular Economy: PSS Conducting the Transition. *Procedia CIRP* **2017**, *64*, 2–6. [CrossRef]
23. Sohal, A.; De Vass, T. Australian SME's experience in transitioning to circular economy. *J. Bus. Res.* **2022**, *142*, 594–604. [CrossRef]
24. Dan, M.C.; Østergaard, T. Circular Fashion: The New Roles of Designers in Organizations Transitioning to a Circular Economy. *Des. J.* **2021**, *24*, 1001–1021. [CrossRef]
25. Wuni, I.Y. Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map. *Build. Environ.* **2022**, *223*, 109453. [CrossRef]
26. Cantú, A.; Aguiñaga, E.; Scheel, C. Learning from Failure and Success: The Challenges for Circular Economy Implementation in SMEs in an Emerging Economy. *Sustainability* **2021**, *13*, 1529. [CrossRef]
27. Honic, M.; Kovacic, I.; Sibenik, G.; Rechberger, H. Data- and stakeholder management framework for the implementation of BIM-based Material Passports. *J. Build. Eng.* **2019**, *23*, 341–350. [CrossRef]
28. Pitkänen, K.; Karppinen, T.K.M.; Kautto, P.; Pirtonen, H.; Salmenperä, H.; Savolahti, H.; Schubin, E.; Myllymaa, T. How to measure the social sustainability of the circular economy? Developing and piloting social circular economy indicators in Finland. *J. Clean. Prod.* **2023**, *392*, 136238. [CrossRef]
29. Debacker, W.; Manshoven, S.; Denis, F. D1 Synthesis of the State-of-the-Art: Key Barriers and Opportunities for Materials Passports and Reversible Building Design in the Current System; BAMB Horizon. 2016. Available online: http://www.bamb2020.eu/wp-content/uploads/2016/03/D1_Synthesis-report-on-State-of-the-art_20161129_FINAL.pdf (accessed on 13 March 2023).
30. Kedir, F.; Bucher, D.F.; Hall, D.M. A Proposed Material Passport Ontology to Enable Circularity for Industrialized Construction. In Proceedings of the EC3 Conference 2021, Online Events, 19–28 July 2021; pp. 91–98.
31. Heinrich, M.; Lang, W. *Materials Passports-Best Practice*; Technische Universität München, Fakultät für Architektur: Munich, Germany, 2019; p. 74.
32. Honic, M.; Kovacic, I.; Rechberger, H. Concept for a BIM-based Material Passport for buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*, 012073. [CrossRef]
33. Plociennik, C.; Pourjafarian, M.; Nazeri, A.; Windholz, W.; Knetsch, S.; Rickert, J.; Ciroth, A.; Precci Lopes, A.D.C.; Hagedorn, T.; Vogelgesang, M.; et al. Towards a Digital Lifecycle Passport for the Circular Economy. *Procedia CIRP* **2022**, *105*, 122–127. [CrossRef]
34. Jensen, S.F.; Kristensen, J.H.; Adamsen, S.; Christensen, A.; Waehrens, B.V. Digital product passports for a circular economy: Data needs for product life cycle decision-making. *Sustain. Prod. Consum.* **2023**, *37*, 242–255. [CrossRef]
35. Hoosain, M.S.; Paul, B.S.; Raza, S.M.; Ramakrishna, S. Material Passports and Circular Economy. In *An Introduction to Circular Economy*; Liu, L., Ramakrishna, S., Eds.; Springer: Singapore, 2021; pp. 131–158, ISBN 9789811585098.
36. Holla, A. *External Supervisor: Monique Fledderman*; VMRG: Nieuwegein, The Netherlands, 2017; p. 180.
37. 3XN Architects. *Buidling a Circular Future*, 3rd ed.; 3XN Architects: Copenhagen, Denmark, 2018.

38. Druijff, B. BIM-Based Material Passport in Madaster during the Operational and Maintenance Phase of a Building. Bachelor's Thesis, University of Twente, Enschede, The Netherlands, 2019.
39. Kintscher, L.; Lawrenz, S.; Poschmann, H. A Life Cycle Oriented Data-Driven Architecture for an Advanced Circular Economy. *Procedia CIRP* **2021**, *98*, 318–323. [CrossRef]
40. Lawrenz, S.; Nippraschk, M.; Wallat, P.; Rausch, A.; Goldmann, D.; Lohrengel, A. Is it all about Information? The Role of the Information Gap between Stakeholders in the Context of the Circular Economy. *Procedia CIRP* **2021**, *98*, 364–369. [CrossRef]
41. Saaksvuori, A.; Immonen, A. *Product Lifecycle Management*; Springer: Berlin/Heidelberg, Germany, 2008; ISBN 978-3-540-78173-8.
42. European Environment Agency. *Circular Economy in Europe: Developing the Knowledge Base*; European Environment Agency: Copenhagen, Denmark, 2016.
43. de Lange, P.; Bähre, B.; Finetti-Imhof, C.; Klamma, R.; Oppermann, L. Socio-Technical Challenges in the Digital Gap between Building Information Modeling and Industry 4.0. In Proceedings of the STPIS@CAiSE, Essen, Germany, 13 June 2017; pp. 33–46.
44. Poirier, E.; Forgues, D.; Staub-French, S. Collaboration through innovation: Implications for expertise in the AEC sector. *Constr. Manag. Econ.* **2016**, *34*, 769–789. [CrossRef]
45. Gotel, O.C.Z.; Finkelstein, C.W. An analysis of the requirements traceability problem. In Proceedings of the IEEE International Conference on Requirements Engineering, Colorado Springs, CO, USA, 18–22 April 1994; IEEE Computer Society Press: Colorado Springs, CO, USA, 1994; pp. 94–101.
46. Wang, K.-S. Intelligent and integrated RFID (II-RFID) system for improving traceability in manufacturing. *Adv. Manuf.* **2014**, *2*, 106–120. [CrossRef]
47. Kamara, J.M.; Anumba, C.J.; Evbuomwan, N.F.O. Establishing and processing client requirements—A key aspect of concurrent engineering in construction. *Eng. Constr. Archit. Manag.* **2000**, *7*, 15–28. [CrossRef]
48. Brandín, R.; Abrishami, S. Information traceability platforms for asset data lifecycle: Blockchain-based technologies. *Smart Sustain. Built Environ.* **2021**, *10*, 364–386. [CrossRef]
49. Riexinger, G.; Doppler, J.P.; Haar, C.; Trierweiler, M.; Buss, A.; Schöbel, K.; Ensling, D.; Bauernhansl, T. Integration of Traceability Systems in Battery Production. *Procedia CIRP* **2020**, *93*, 125–130. [CrossRef]
50. Mora-Cantallops, M.; Sánchez-Alonso, S.; García-Barriocanal, E.; Sicilia, M.-A. Traceability for Trustworthy AI: A Review of Models and Tools. *Big Data Cogn. Comput.* **2021**, *5*, 20. [CrossRef]
51. Pinheiro, C. Requirements traceability. *Perspect. Softw. Requir.* **2004**, 91–113. [CrossRef]
52. Folinas, D.; Manikas, I.; Manos, B. Traceability data management for food chains. *Br. Food J.* **2006**, *108*, 622–633. [CrossRef]
53. Zhou, W.; Piramuthu, S. IoT and Supply Chain Traceability. In *Future Network Systems and Security*; Doss, R., Piramuthu, S., Zhou, W., Eds.; Communications in Computer and Information Science; Springer International Publishing: Cham, Switzerland, 2015; Volume 523, pp. 156–165, ISBN 978-3-319-19209-3.
54. Bougdira, A.; Akharraz, I.; Ahaitouf, A. A traceability proposal for industry 4.0. *J. Ambient Intell. Humaniz. Comput.* **2020**, *11*, 3355–3369. [CrossRef]
55. Jansen-Vullers, M.H.; van Dorp, C.A.; Beulens, A.J.M. Managing traceability information in manufacture. *Int. J. Inf. Manag.* **2003**, *23*, 395–413. [CrossRef]
56. Li, X.; Lv, F.; Xiang, F.; Sun, Z.; Sun, Z. Research on Key Technologies of Logistics Information Traceability Model Based on Consortium Chain. *IEEE Access* **2020**, *8*, 69754–69762. [CrossRef]
57. Aiello, G.; Enea, M.; Muriana, C. The Expected Value of the Traceability Information. *Eur. J. Oper. Res.* **2015**, *244*, 176–186. [CrossRef]
58. Mader, P.; Gotel, O.; Philippow, I. Getting back to basics: Promoting the use of a traceability information model in practice. In Proceedings of the 2009 ICSE Workshop on Traceability in Emerging Forms of Software Engineering, Vancouver, BC, Canada, 18 May 2009; IEEE: Vancouver, BC, Canada, 2009; pp. 21–25.
59. Dalvit, C.; De Marchi, M.; Cassandro, M. Genetic traceability of livestock products: A review. *Meat Sci.* **2007**, *77*, 437–449. [CrossRef]
60. Dalvit, C.; De Marchi, M.; Targhetta, C.; Gervaso, M.; Cassandro, M. Genetic Traceability of Meat Using Microsatellite Markers. *Food Res. Int.* **2008**, *41*, 301–307. [CrossRef]
61. Bonizzi, I.; Feligini, M.; Aleandri, R.; Enne, G. Genetic traceability of the geographical origin of typical Italian water buffalo Mozzarella cheese: A preliminary approach. *J. Appl. Microbiol.* **2007**, *102*, 667–673. [CrossRef] [PubMed]
62. Lago, P.; Muccini, H.; van Vliet, H. A scoped approach to traceability management. *J. Syst. Softw.* **2009**, *82*, 168–182. [CrossRef]
63. Cleland-Huang, J.; Gotel, O.C.Z.; Huffman Hayes, J.; Mäder, P.; Zisman, A. Software traceability: Trends and future directions. In Proceedings of the Future of Software Engineering Proceedings, Hyderabad, India, 31 May–7 June 2014; ACM: Hyderabad, India, 2014; pp. 55–69.
64. Cleland-Huang, J.; Chang, C.K.; Christensen, M. Event-based traceability for managing evolutionary change. *IEEE Trans. Softw. Eng.* **2003**, *29*, 796–810. [CrossRef]
65. Cleland-Huang, J.; Chang, C.K.; Ge, Y. Supporting Event Based Traceability through High-Level Recognition of Change Events. In Proceedings of the 26th Annual International Computer Software and Applications, Oxford, UK, 26–29 August 2002; IEEE Computer Society: Oxford, UK, 2002; pp. 595–600.

66. Cleland-Huang, J.; Chang, C.K.; Sethi, G.; Javvaji, K.; Haijian, H.; Jinchun, X. Automating speculative queries through event-based requirements traceability. In Proceedings of the IEEE Joint International Conference on Requirements Engineering, Essen, Germany, 9–13 September 2002; IEEE Computer Society: Essen, Germany, 2002; pp. 289–296.
67. Pauzi, Z.; Capiluppi, A. Applications of natural language processing in software traceability: A systematic mapping study. *J. Syst. Softw.* **2023**, *198*, 111616. [CrossRef]
68. Cleland-Huang, J.; Marrero, W.; Berenbach, B. Goal-Centric Traceability: Using Virtual Plumblines to Maintain Critical Systemic Qualities. *IEEE Trans. Softw. Eng.* **2008**, *34*, 685–699. [CrossRef]
69. Islam, S.; Manning, L.; Cullen, J.M. A Hybrid Traceability Technology Selection Approach for Sustainable Food Supply Chains. *Sustainability* **2021**, *13*, 9385. [CrossRef]
70. Wang, J.; Wang, J.-M.; Zhang, Y.-J. Agricultural Product Quality Traceability System Based on the Hybrid Mode. In Proceedings of the 2018 4th Annual International Conference on Network and Information Systems for Computers (ICNISC), Wuhan, China, 19–21 April 2018; IEEE: Wuhan, China, 2018; pp. 392–395.
71. Wang, S.; Li, T.; Yang, Z. Exploring Semantics of Software Artifacts to Improve Requirements Traceability Recovery: A Hybrid Approach. In Proceedings of the 2019 26th Asia-Pacific Software Engineering Conference (APSEC), Putrajaya, Malaysia, 2–5 December 2019; IEEE: Putrajaya, Malaysia, 2019; pp. 39–46.
72. de Lusignan, S.; Liaw, S.-T.; Krause, P.; Curcin, V.; Vicente, M.; Michalakidis, G.; Agreus, L.; Leysen, P.; Shaw, N.; Mendis, K. Key Concepts to Assess the Readiness of Data for International Research: Data Quality, Lineage and Provenance, Extraction and Processing Errors, Traceability, and Curation: Contribution of the IMIA Primary Health Care Informatics Working Group. *Yearb. Med. Inform.* **2011**, *20*, 112–120. [CrossRef]
73. Pearson, S.; May, D.; Leontidis, G.; Swainson, M.; Brewer, S.; Bidaut, L.; Frey, J.G.; Parr, G.; Maull, R.; Zisman, A. Are Distributed Ledger Technologies the panacea for food traceability? *Glob. Food Secur.* **2019**, *20*, 145–149. [CrossRef]
74. Moe, T. Perspectives on Traceability in Food Manufacture. *Trends Food Sci. Technol.* **1998**, *9*, 211–214. [CrossRef]
75. Senneset, G.; Forås, E.; Fremme, K.M. Challenges regarding implementation of electronic chain traceability. *Br. Food J.* **2007**, *109*, 805–818. [CrossRef]
76. Anastasiadis, F. Designing a Traceability Framework for Sustainable Agri-Food Supply Chains. In *Food Policy Modelling*; Mattas, K., Baourakis, G., Zopounidis, C., Staboulis, C., Eds.; Cooperative Management; Springer International Publishing: Cham, Switzerland, 2022; pp. 73–82, ISBN 978-3-031-08316-7.
77. Glass, J.; Achour, N.; Parry, T.; Nicholson, I. Engaging small firms in sustainable supply chains: Responsible sourcing practices in the UK construction industry. *Int. J. Agile Syst. Manag.* **2012**, *5*, 29. [CrossRef]
78. Wohlrab, R.; Steghofer, J.-P.; Knauss, E.; Maro, S.; Anjorin, A. Collaborative Traceability Management: Challenges and Opportunities. In Proceedings of the 2016 IEEE 24th International Requirements Engineering Conference (RE), Beijing, China, 12–16 September 2016; IEEE: Beijing, China, 2016; pp. 216–225.
79. Ramesh, B.; Jarke, M. Toward reference models for requirements traceability. *IEEE Trans. Softw. Eng.* **2001**, *27*, 58–93. [CrossRef]
80. Ouertani, M.Z.; Baïna, S.; Gzara, L.; Morel, G. Traceability and management of dispersed product knowledge during design and manufacturing. *Comput.-Aided Des.* **2011**, *43*, 546–562. [CrossRef]
81. BRE Global Ltd. *BES 6001: ISSUE 3.0*; Framework Standard for Responsible Sourcing; BREGroup: Watford, UK, 2014.
82. Norton, T.; Beier, J.; Shields, L. A Guide to Traceability. 2014. Available online: https://bregroup.com/services/standards/bes-6001-the-framework-standard-for-responsible-sourcing/ (accessed on 25 March 2023).
83. Beliatis, M.J.; Jensen, K.; Ellegaard, L.; Aagaard, A.; Presser, M. Next Generation Industrial IoT Digitalization for Traceability in Metal Manufacturing Industry: A Case Study of Industry 4.0. *Electronics* **2021**, *10*, 628. [CrossRef]
84. EU. EEA Regulation (EU) No 305/2011 of the European Parliament and of the Council. EUR-Lex; 2011. Available online: https://www.legislation.gov.uk/eur/2011/305/contents (accessed on 20 March 2023).
85. Wright, B. Compilation of Various Questions and Answers about EPA Traceability Protocol for Gaseous Calibration Standards. 2020. Available online: https://www.epa.gov/sites/default/files/2020-04/documents/questions_answers_protocol_200331.pdf. (accessed on 20 March 2023).
86. Sarsam, S.I. Sustainable and Green Roadway Rating System. *Int. J. Sci. Res. Environ. Sci.* **2015**, *3*, 99–106. [CrossRef]
87. Pang, T.Y.; Pelaez Restrepo, J.D.; Cheng, C.-T.; Yasin, A.; Lim, H.; Miletic, M. Developing a Digital Twin and Digital Thread Framework for an 'Industry 4.0′ Shipyard. *Appl. Sci.* **2021**, *11*, 1097. [CrossRef]
88. Li, J.; Kassem, M.; Watson, R. A Blockchain and Smart Contract-Based Framework to Inrease Traceability of Built Assets. In Proceedings of the 37th CIB W78 Information Technology for Construction Conference (CIB W78), São Paulo, Brazil, 2–4 June 2020; pp. 347–362.
89. Wang, Z.; Wang, T.; Hu, H.; Gong, J.; Ren, X.; Xiao, Q. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Autom. Constr.* **2020**, *111*, 103063. [CrossRef]
90. Toriello, M. Creating the Digital Thread. *INSIGHT* **2022**, *25*, 34–37. [CrossRef]
91. Wang, J.; Chi, H.-L.; Shou, W.; Chong, H.-Y.; Wang, X. A Coordinated Approach for Supply-Chain Tracking in the Liquefied Natural Gas Industry. *Sustainability* **2018**, *10*, 4822. [CrossRef]
92. Ergen, E.; Akinci, B.; Sacks, R. Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. *Autom. Constr.* **2007**, *16*, 354–367. [CrossRef]

93. Durmiševic', E. Reversible building design. In *Designing for the Circular Economy*; Charter, M., Ed.; Routledge: Abingdon, UK; New York, NY, USA, 2018; pp. 344–359, ISBN 978-1-315-11306-7.
94. Morseletto, P. Targets for a circular economy. *Resour. Conserv. Recycl.* **2020**, *153*, 104553. [CrossRef]
95. Succar, B.; Poirier, E. Lifecycle information transformation and exchange for delivering and managing digital and physical assets. *Autom. Constr.* **2020**, *112*, 103090. [CrossRef]
96. Succar, B. Information Milestone. Available online: https://bimdictionary.com/en/information-milestone/1 (accessed on 20 March 2023).
97. Wohlrab, R.; Knauss, E.; Steghöfer, J.-P.; Maro, S.; Anjorin, A.; Pelliccione, P. Collaborative traceability management: A multiple case study from the perspectives of organization, process, and culture. *Requir. Eng.* **2020**, *25*, 21–45. [CrossRef]
98. Ramesh, B. Process Knowledge Management with Traceability. *IEEE Softw.* **2002**, *19*, 50–52. [CrossRef]
99. Bozoglu, J. Collaboration and coordination learning modules for bim education. *J. Inf. Technol. Constr.* **2016**, *21*, 152–163.
100. Gotel, O.; Cleland-Huang, J.; Hayes, J.H.; Zisman, A.; Egyed, A.; Grunbacher, P.; Antoniol, G. The quest for Ubiquity: A roadmap for software and systems traceability research. In Proceedings of the 2012 20th IEEE International Requirements Engineering Conference (RE), Chicago, IL, USA, 24–28 September 2012; IEEE: Chicago, IL, USA, 2012; pp. 71–80.
101. Liu, H. Combating unethical producer behavior: The value of traceability in produce supply chains. *Int. J. Prod. Econ.* **2022**, *244*, 108374. [CrossRef]
102. Mejías, A.M.; Bellas, R.; Pardo, J.E.; Paz, E. Traceability management systems and capacity building as new approaches for improving sustainability in the fashion multi-tier supply chain. *Int. J. Prod. Econ.* **2019**, *217*, 143–158. [CrossRef]
103. Rival, A.; Montet, D.; Pioch, D. Certification, labelling and traceability of palm oil: Can we build confidence from trustworthy standards? *OCL* **2016**, *23*, D609. [CrossRef]
104. Dömges, R.; Pohl, K. Adapting traceability environments to project-specific needs. *Commun. ACM* **1998**, *41*, 54–62. [CrossRef]
105. Walden, J.; Steinbrecher, A.; Marinkovic, M. Digital Product Passports as Enabler of the Circular Economy. *Chem. Ing. Tech.* **2021**, *93*, 1717–1727. [CrossRef]
106. Alani, Y.; Dawood, N.; Patacas, J.; Rodriguez, S.; Dawood, H. A semantic common model for product data in the water industry. *J. Inf. Technol. Constr.* **2021**, *26*, 566–590. [CrossRef]
107. Lucky, M.N.; Pasini, D.; Spagnolo, S.L. Product Data Management for Sustainability: An Interoperable Approach for Sharing Product Data in a BIM Environment. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *296*, 012053. [CrossRef]
108. Eadie, R.; Browne, M.; Odeyinka, H.; McKeown, C.; McNiff, S. BIM implementation throughout the UK construction project lifecycle: An analysis. *Autom. Constr.* **2013**, *36*, 145–151. [CrossRef]
109. Jiang, S.; Jiang, L.; Han, Y.; Wu, Z.; Wang, N. OpenBIM: An Enabling Solution for Information Interoperability. *Appl. Sci.* **2019**, *9*, 5358. [CrossRef]
110. Shafiq, M.T.; Matthews, J.; Lockley, S.R. A study of BIM collaboration requirements and available features in existing model collaboration systems. *J. Inf. Technol. Constr.* **2013**, *18*, 148–161.
111. Kwon, S.; Monnier, L.V.; Barbau, R.; Bernstein, W.Z. Enriching standards-based digital thread by fusing as-designed and as-inspected data using knowledge graphs. *Adv. Eng. Inform.* **2020**, *46*, 101102. [CrossRef]
112. Singh, V.; Willcox, K.E. Engineering Design with Digital Thread. *AIAA J.* **2018**, *56*, 4515–4528. [CrossRef]
113. David, J.; Jarvenpaa, E.; Lobov, A. Digital Threads via Knowledge-Based Engineering Systems. In Proceedings of the 2021 30th Conference of Open Innovations Association FRUCT, Oulu, Finland, 27–29 October 2021; IEEE: Oulu, Finland, 2021; pp. 42–51.
114. O'Grady, T.M.; Brajkovich, N.; Minunno, R.; Chong, H.-Y.; Morrison, G.M. Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction. *Energies* **2021**, *14*, 4065. [CrossRef]
115. Xue, K.; Hossain, M.U.; Liu, M.; Ma, M.; Zhang, Y.; Hu, M.; Chen, X.; Cao, G. BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review. *Sustainability* **2021**, *13*, 1310. [CrossRef]
116. Zahrizan, Z.; Ali, N.M.; Haron, A.T.; Marshall-Ponting, A.; Hamid, Z.A. Exploring the adoption of building information modelling (BIM) in the malaysian construction industry: A qualitative approach. *Int. J. Res. Eng. Technol.* **2013**, *2*, 384–395. [CrossRef]