BLOCKCHAIN SUPPORTED CLOSED LOOP IN CIRCULAR ECONOMY

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Abstract

Existing challenges in policy, practice, and digital innovation, and their integration into Circular Economy (CE) result in a complex undertaking. Currently, not many frameworks for the digital optimization of a building's End-of-Life (EoL) and its related processes exist. This paper explores the digitalization of the EoL process with blockchain technology, by analysing an applied use case of a closed loop reuse product in Austria. A blockchain-based solution designed to enhance the verifiability of the reuse process is proposed, by introducing a privacy-preserving zero-knowledge proof application which can increase, among other things, transparency, and trust to promote CE.

Introduction

The transition towards a Circular Economy (CE) represents a paradigm shift from traditional, linear economic models towards ones that are restorative and regenerative by design (Bocken et al. 2016; Kirchherr et al. 2023). This shift is underpinned by the integration of digital technologies, which play a pivotal role in enhancing the sustainability and efficiency of various sectors, from waste management to construction (Kamble et al. 2018). The End-of-Life (EoL) process of products and materials is a critical aspect of the CE and gets increasingly important due to resource shortages and CO_2 emissions benchmarks (Gervasio & Dimova 2018) for certification of buildings (e.g. DGNB), also required for compliance with the EU Taxonomy (2024) for buildings. With the gradual digitalization of EoL processes (Dodampegama et al. 2024) a fundamental database can be created to promote recycling, reuse, and reduction of construction demolition waste (Papamichael et al. 2023), contributing to the conservation of resources and the mitigation of environmental pollution.

Studies like Pagoropoulos et al. (2017) emphasize the role of digital technologies, including Big Data and IoT, in advancing CE. Additionally, in the construction sector, digital platforms for Circular Economy are aimed at integrating digital technologies and data management to optimize resource use, addressing the industry's challenges (Kovacic et al. 2020). Findings from Çetin et al. (2022), highlight the potential of digital twins and scanning technologies in supporting CE strategies despite existing challenges. These insights underscore the digitalization's crucial role in advancing CE, calling for continued exploration and application of digital solutions.

This paper explores the digitalization of the EoL process with blockchain technology by analysing a use case of a closed-loop reuse-product, applied in Austria. This blockchain-based solution is designed to enhance the digital perspective of the reuse process, by introducing a verifiable certification concept. This concept ensures the correctness of provided claims without breaking privacy for the involved stakeholders, with zero-knowledge proofs. In this way the solution increases, among other things, transparency and trust to promote CE implementation.

Literature Background

Circular Economy

Kircher et al. (2017) present a comprehensive definition of CE derived from extensive literature review. They define CE as an economic system that shifts away from the EoL concept by prioritizing reduction, reuse, recycling, and recovery of materials throughout the production, distribution, and consumption processes. This operates at various levels including micro (products, companies, consumers), meso (eco-industrial parks), and macro (city, region, nation, and beyond), facilitated by innovative business models and responsible consumer behaviour. Consequently, there are diverse interpretations of CE and circularity (Kirchherr et al. 2017; Alhawari et al. 2021), all aiming at incorporating strategies for smarter product use (refuse, rethink, reduce), longer product lifetimes (reuse, quality, repair), and material circulation at the EoL (recycling, cascading), necessitating new business models for implementation (Brändström & Eriksson 2022).

In Architecture, Engineering, and Construction (AEC), the building life cycle comprises four stages (EN 15978:2011): production, construction, use, End-of-Life including deconstruction/demolition, transport, waste processing, and disposal. Currently, the EoL phase of the buildings' life cycle remains the least sustainable (Charef 2022). Defining End-of-Life within the CE context in AEC poses challenges due to the lack of clear standardization and regulation across different countries, and essential prerequisites for digitalization including the use of Building Information Modeling (BIM). The disconnection between BIM tools and EoL tools hampers comprehensive considerations of this phase (Akbarieh et al. 2020). The built environment represents a significant, yet poorly documented stock of material resources (Heisel & Rau-Oberhuber 2020). Absence of guidelines for material and component databases impedes conclusions drawn from EoL considerations, which should ideally be integrated into the design phase. Adopting circular design strategies (e.g., design for deconstruction, disassembly, adaptability, and flexibility) alone does not reduce environmental impact unless integrated and considered during the design phase to manifest in whole buildings' life cycle. Moreover, EoL asset management necessitates extensive data, requiring new workflows, processes, and business models (Charef 2022).

The digital potential within the reuse process, highlights how advancements in Artificial Intelligence and BIM are unlocking new possibilities for effective reuse strategies in the construction sector (Khosrowshahi, 2017). Initiatives like the EU-funded RRReMaker project, employ Artificial Intelligence for design for deconstruction, aimed at resolving current problems when planning with reuse components and their associated uncertainties such as quality etc. Simpler versions of digitalization are online platforms for reuse (e.g. Harvest Map; Concular), which are increasing in number and significance, and facilitating material reuse, especially with the goal of shifting the paradigm of this topic in society. The success of these platforms depends on the provision of comprehensive and detailed information about available materials, their provenance in combination with material condition (Veit et al. 2014).

The legal framework for CE in Austria is mainly regulated in the Austrian Waste Management Act (AWG 2002), which introduces a waste hierarchy. In addition, the Austrian standard *Dismantling of buildings as standard method for demolition* (ÖNORM B3151:2022) is applied on a voluntary basis, and gives a guideline on how to proceed in the building's EoL: demolition typically follows the reverse sequence of construction, focusing on maximizing reuse, preparation for reuse, or recycling of materials resulting from the process.

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Closed Loop in CE

The closed-loop system is an integral part of the CE, and it stands in contrast to the traditional linear economy, which follows a *take, make, dispose* (EMF 2013) model of production. By maintaining the utility and value of products through multiple life cycles, closed loop systems can significantly reduce environmental impact by lowering the demand for resource extraction and minimizing waste. Moreover, closed loop practices can lead to economic benefits by reducing the raw material procurement and waste disposal. Socially, they can contribute to job creation in the refurbishment and maintenance sectors (Zhang et al. 2024).

Braungart et al. (2008) differentiate between *cradle-to-grave* flows of materials and cyclical, *cradle-to-cradle* flows, whereby Stahel (1982; 1994, p.179; 2010) refers to *closed loop systems* instead of cyclical systems, introducing herewith two essentially different types of loops within a closed loop system (1) reuse of goods and (2) recycling of materials. Referring to the aforementioned authors including McDonough & Braungart (2002), Bocken et al. (2016, p. 309) define two cardinal strategies for the cycling of resources: 1) *slowing resource loops* - By crafting durable goods and implementing strategies like product-life extension, such as service loops for repairs and remanufacturing, the lifespan of products is prolonged, leading to a reduction in the rate of resource consumption; 2) *closing resource loops* - Recycling closes the loop between post-use and production, establishing a circular flow of resources.

In a closed loop system, the End-of-Life concept is replaced with restoration/refurbishment; products must be designed with their next use in mind. This means that once the initial use of a product is completed, it can be disassembled and the materials can be used again in their original form instead of being downcycled into lower-quality applications (Braungart et al. 2007).

However, the transition to a closed loop system is not without challenges. It requires a paradigm shift in design philosophy, a move towards business models that can support product life extension, and the development of markets for secondary materials. It also depends on the establishment of effective collection and processing systems that can support the return of used products for remanufacturing or recycling (Korhonen et al. 2018; Figge et al. 2023).

Expanded from Bocken et al. (2016, p. 309), for the purpose of the presented research, Figure 1 shows a circular life extension of a good/product in CE where the left section (black) demonstrates a system focused on waste recycling. The complete picture however, which

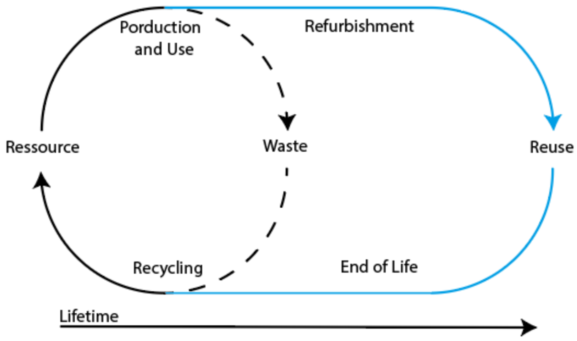

Figure 1: Closed Loop in CE

includes the right side (blue), reveals a fully realized CE that emphasizes keeping goods/products in use for as long as possible (extending the life span) through refurbishment and therefore in a closed loop system. The concept begins with resource extraction and product use, followed by product recycling at the end of its life. The expansion into refurbishment aims at slowing down the resource loop, hence promoting reuse and reducing the dependence on new resources.

Blockchain in EoL

Blockchain technology, synonymous with Distributed Ledger Technology (DLT) and initially introduced through Bitcoin (Nakamoto, 2008), has gained momentum across various sectors. Although the term was originally coined to describe Bitcoin's data structure, it now encompasses the underlying technology that permits decentralized state synchronization. This encompasses not only account balances, as with Bitcoin, but also a range of data types where the current state is critical for all participants. DLT's utility is further enhanced by Smart Contracts (Szabo 1997), with Ethereum blockchain (Buterin et al. 2013) emerging as the standard-bearer for Smart Contracts (SC) execution.

Blockchains, particularly in their original iterations like Bitcoin and Ethereum, operate as open networks with public data visibility. In contrast, private blockchains, which are generally permissioned and limit data access to known participants, are considered more appropriate for corporate use (Wüst et al. 2017). However, the efficacy of private blockchains has been questionable, potentially due to the absence of a "network effect." A hybrid approach that utilizes SCs on public networks alongside private databases interfacing through standardized protocols may offer a resolution.

Several studies illustrate blockchains potential to boost the life cycle approach within the AEC sector (Scott et al. 2021). Blockchain can ensure comprehensive traceability of materials and energy, aiding in the prediction of recycling and reuse outcomes for materials utilized in construction (Shojaei et al. 2021). The technology can also enhance the transparency and reliability of data in Environmental Product Declarations - EPDs (Rangelov et al. 2021). It facilitates end-to-end lifecycle assessment by documenting the metadata of raw materials, thereby verifying their provenance from source to construction site (Shojaei 2019). Copeland and Bilec (2020) have integrated RFID, BIM, and blockchain to specify components with a verifiable data trail throughout their lifecycle, and explored the integration with a crypto-economic incentive model for asset recycling. Additionally, blockchains can be employed for post-occupancy evaluations, with BIM serving as the repository and blockchain as the validator for built environment assets (Di Giuda et al. 2020).

Methodology

The presented research follows an integrated research approach, which, in a first step, was based on a comprehensive literature review, secondly on conducted and evaluated interviews with key stakeholders operating in AEC and EoL. These findings laid the groundwork for the following use case analysis of a reuse product in a CE closed loop, as outlined in the literature background. Furthermore, an important element of this ongoing research within the realm of the DiCYCLE project, is the integration of a blockchain into the framework of the presented use case called re:parkett. To create the presented use case, a workshop was conducted, where the details of the individual process steps were documented, and the current challenges in CE were discussed. The latter were the starting point for the applicability of our framework. The focus was on ensuring that the “executed” process was true to the “planned” process enabling herewith transparency and authenticity verification of the reuse product. In addition, a proposal for the creation of CO_2 certificates for the reuse product is laid out, adding also economic value, based on the partially required CO_2-audits for buildings. The aim is therefore to enable the creation of an unfalsifiable proof that the parquet flooring has been reused and is a closed loop product as shown in the case of re:parkett.

Use Case re:parkett

The starting point for re:parkett was the dismantling of significant areas of parquet flooring at the former Vienna Directorate and subsequently the requirements of a new project that needed installation of approximately 1200 square meters of parquet flooring for a building contractor in St. Pölten, Austria. This resulted in the novel idea of mechanically processing and further refurbishing individual parquet strips for reuse in new building projects.

In collaboration with a floor manufacturer, this concept transitioned into an implementation phase focused on product development. The objective was set to install 500 square meters of the reuse product by the end of 2022. A key aspect of this activity was the partnership with a floor laying company, which played a crucial role in both the dismantling and installation processes, thereby closing the loop of the product cycle. To ensure a systematic approach to the dismantling process, all three involved companies (the “circular design” company responsible for the assessment and collection of reusable parquet flooring, the manufacturer of flooring and the parquet floor layer) aimed at developing a manual that would integrate a standardized harvesting process into their business models. By April 2022, the first sample of the processed parquet was showcased publicly, signalling the readiness for market introduction. Efforts to expand distribution channels across various regions are ongoing, reflecting a scalable model for the adoption of sustainable practices in construction and renovation projects. This use case exemplifies the potential of collaborative innovation in promoting CE principles within the AEC industry.

Use Case Analysis & Discussion

In the research project DiCYCLE, a systematic approach to reprocessing harvested parquet floors has been developed, encompassing several key steps, as shown in Figure 2. The process is divided into four levels, with transport, deconstruction, manufacturing and certification. It initiates upon receiving an order, where builders, flooring layers, or flooring owners seek out the services of a company skilled to perform dismantling, recovery, or reprocessing of used/old parquet flooring. The second step involves a detailed and professional inventory of an existing or potential repository, with an assessment of the current condition of parquet flooring. Hence, an expert determines data regarding quantity, quality, and other features of the parquet, which are documented in a data sheet. Additionally, external parties can submit their own data sheets of potential repositories of reusable parquet flooring to the online platform/database (e.g. Harvest Map) of the "circular design" company which is then further checked and processed.

A crucial decision is made based on the collected information: whether to renovate the parquet flooring on-site, dismantle it for reuse, or dispose of it. In scenarios, where on-site renovation is deemed feasible, sometimes there might be a shift into dismantling and processing of flooring into a reuse product, due to previously false classification or the parquet owner's change of plans. However, in some cases this leads to improper dismantling by untrained individuals due to time or budget constraints, potentially reducing the amount of material available for reuse.

In the "circular design" company's database (Harvest Map) all relevant data on the dismantled parquet flooring regarding, quality and quantity is collected. However, the following step, which should entail an automatic digital data transfer between the "source database" and the manufacturer responsible for the refurbishment of the reusable parquet flooring, is currently missing due to the absence of a suitable implementable solution.

Going further into the process the manufacturer after receiving data regarding quality and availability of the flooring area, integrates this information into its own Enterprise Resource Planning (ERP) system, which is then utilized to determine the market demand for the product, as well as production plans and associated sales activities.

To summarize, the final decision on demolition or delivery to the manufacturer, is based on all previous steps in the laid-out process by the "circular design" company. For existing buildings, demolition is initiated, or the inventory in stock is delivered to the manufacturer for further processing. The dismantled product is then handled in the manufacturer's own production facility deemed at restoring/refurbishing the product, eventually ending up either being stored in the manufacturer's own warehouse or sold directly to the customers on demand, depending on the sales planning and production capacities.

In addition to all these steps, there is currently an ongoing effort to create a CO_2 certificate in the form of an EPD for the finished reuse product. This initiative aims to quantify the environmental impacts across all process steps, potentially offering the certificate with the floor delivery, or positioning the closed loop product on the market with its environmental background information. As mentioned, the schematic process is illustrated in Figure 2, providing an overview of the approach adopted in the DiCYCLE project.

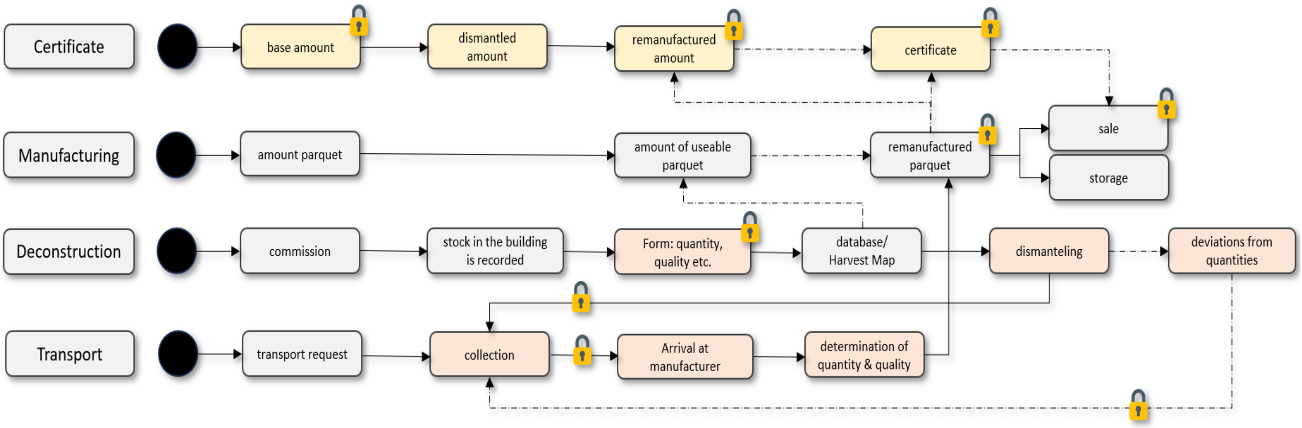

Figure 2: re:parkett process analysis

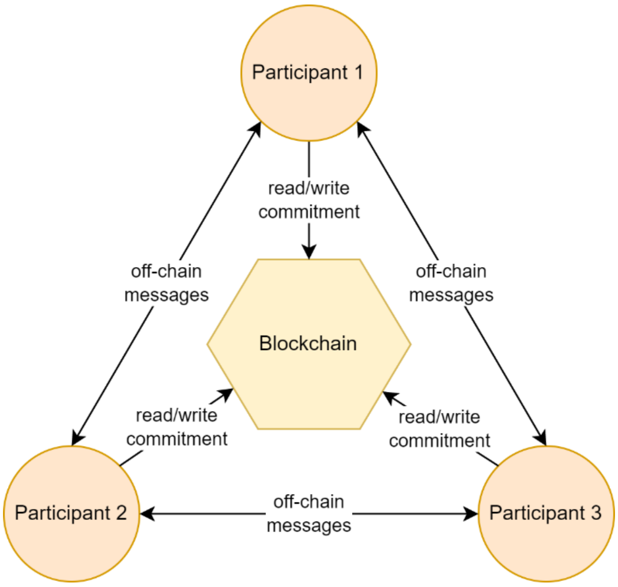

Figure 3: Overview of interactions on the blockchain

Blockchain application

Based on findings from the projects BIM.design & FMChain and the ongoing research presented here, we developed a system architecture for the use of blockchain to address challenges in the EoL process. The proposed framework allows for sustainable documentation of essential steps and data in the EoL value chain and ensures verifiable compliance to process models.

The first use of blockchain technology in the field of business process management mapped processes models entirely on blockchains by translating models to Smart Contracts (Weber et. al. 2016, García-Bañuelos et. al. 2017, López-Pintado et. al. 2019). This initial approach of mapping all data (including actors, gateways, etc.) on the blockchain is problematic for several reasons: Generally, when implementing processes, which involve multiple stakeholders, two fundamental obstacles occur. Firstly, basic privacy requirements of companies are violated: companies generally want to avoid having their own data associated with their business processes (e.g. supply chain data, production process data, etc.) to be openly visible to third parties. This was also reaffirmed by our interview partners in our requirements analysis for our use case. Furthermore, storing data on a blockchain is also unattractive due to high transaction costs. This is especially true for so called public blockchains, like Bitcoin or Ethereum. These are, as the name suggests, visible and open to be used by everyone. However, this is also a disadvantage, since the limited possible number of transactions per second can result in high transaction costs for participants. Private blockchains, i.e., blockchains that cannot be viewed by everyone and are operated by a small number of participants, have this limitation to a much lesser extent, but have other disadvantages, such as missing network effects; and also lack the capability for public verification (Carminati et. al. 2018, Marangone et. al. 2022).

In summary, as little data as possible should be stored on the blockchain but enough to fully exploit the capabilities of this technology. The data on the blockchain should also meet the privacy requirements.

With that in mind, Figure 3 shows our developed framework and how participants interact with the blockchain and each other. The main communication between the individual participants takes place off-chain, i.e. using peer-to-peer communication channels. The interaction with the blockchain is limited to commitments that represent irrevocable statements. These need to be transparent and verifiable for everyone and are therefore stored on the blockchain. These statements include only a fraction of the data that is held by the individual participants. A zero-knowledge proof (ZKP) ensures the relation between the commitments and the private data as well as the correct execution of state updates. The private data hence becomes immutable and tamper-proof.

To harness these privacy and security features in our framework we model use cases as a choreography of message exchanges. Figure 4 displays the message exchanges of an End-of-Life value chain, based on our use case re:parkett in a simplified form as a BPMN choreography diagram. Each box represents a message exchange task and displays the two stakeholders in terms of sender and recipient, as well as the conducted action. This modelling method results in a clear definition of the order in which stakeholders are involved and the information being shared between them. The interaction with the blockchain is limited to essential commitments

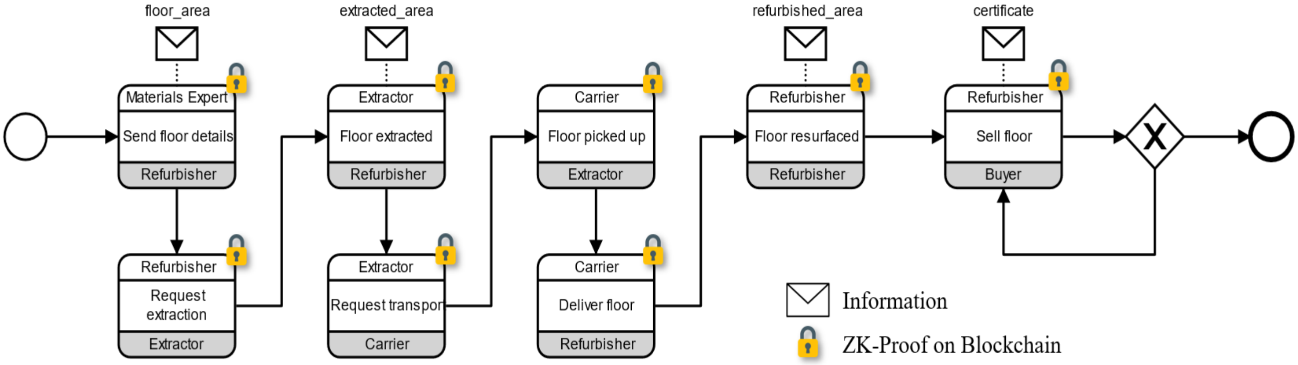

Figure 4: BPNM choreography diagram for re:parkett

and associated ZKPs (illustrated as padlocks in Fig. 2 and Fig. 4), verified with a smart contract on the blockchain. This facilitates immutable and public-verifiable assignment of data, without revealing any additional or non-disclosable private information.

A Zero-Knowledge Proof (ZKP) is set up as an interaction between a prover and a verifier. The prover's goal is to convince the verifier of the correctness of a computation without revealing the complete set of inputs (Goldreich and Oren 1994; Tomaz et al. 2020). ZKPs therefore provide the fundamentals to secure authentication and privacy protection in blockchain transactions, by creating a platform for stakeholders to interact without disclosing sensitive data (Meralli, 2020; Čapko et al. 2022).

While ZKPs were envisioned as multi-round interactive protocols, current variants are non-interactive i.e., only a single message is exchanged between the prover and the verifier. This property allows ZKPs to be included in blockchain transactions. Furthermore, zk-SNARKs, a highly efficient non-interactive variant with small proof sizes, enable storage and verification on the blockchain (Partala et. al. 2020).

Our framework utilizes this technique to ensure the correctness of private processes on a public blockchain. More specifically, participants signal the completion of a choreography tasks by sending off-chain messages to each other. Furthermore, they commit to those messages by sending a transaction consisting of a reference to the message and the process state together with a ZKP to the blockchain. A Smart Contract verifies the correctness of the ZKP and only updates the process state in case of success. The ZKP ensures that only transitions defined in the model can be executed, that only the permissioned participants can trigger a transition, and that the passed information satisfies some predefined rules. For example, in the case of the re:parkett use case, only the *Extractor* may complete the *Floor extracted* task by sending a message to the *Refurbisher*. Furthermore, although not shown in the figure, the value of *extracted_area* needs to be smaller or equal to the *floor_area* value that was provided by the *Materials Expert* in the first task.

Applied to the whole re:parkett use case the framework allows to create a certificate of provenance. A reference to the state in the SC proofs the validity of the certificate, as only conforming process updates can be submitted to the blockchain and hence the claims of the certificates must be correct. In case of re:parkett the certificate ensures that the amount of floor certified as recycled cannot exceed the amount identified by the expert.

The example demonstrates that our framework is highly suitable for many supply-chain use cases in AEC. By adopting our approach of tracing goods, it becomes feasible to comply with privacy requirements and legislation, while increasing the level of trust and security for digital processes in CE.

Conclusion

In this paper, we have explored the integration of blockchain technology into EoL processes within a CE framework, using a specific case study of a closed-loop reuse-product in Austria. The application of a blockchain-based solution has demonstrated substantial potential to enhance challenges regarding transparency, authenticity and trust through verifiable, privacy-preserving mechanisms, specifically zero-knowledge proofs.

Our research confirms that digital technologies, like blockchain, are vital for advancing CE by ensuring transparent and reliable data throughout product and material lifecycles. Implementing our blockchain framework in parquet flooring reuse demonstrates effective digital strategies for real-world CE challenges. This enhances environmental sustainability and creates economic value by potentially generating CO2 certificates (e.g. possibly published on a token, referring to CO2 emissions of a product or part of a product), herewith aligning with EU Taxonomy compliance. The findings support stronger integration of digital tools in CE processes, especially in the building sector, for resource efficiency improvements.

Ultimately, this paper calls for ongoing research and collaboration across sectors to refine and expand the use of digital solutions in promoting sustainable practices within the circular economy. This will not only enhance environmental outcomes but also foster economic resilience and social well-being.

Acknowledgments

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References

Alhawari, O., Awan, U., Bhutta, M. K. S. & Ülkü, M. A. (2021). Insights from Circular Economy Literature: A Re-view of Extant Definitions and Unravelling Paths to Fu-ture Research. Sustainability, 13(2): 859.

Akbarieh, A., Jayasinghe, L. B., Waldmann, D. & Teferle, F. N. (2020). BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review. Sustainability, 12(7): 2670.

AWG (2002): Abfallwirtschaftsgesetz 2002. https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20002086

Braungart, M., McDonough, W. & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design, Journal of Cleaner Production, Volume 15, Issues 13–14, Pages 1337-1348, ISSN 0959-6526, 10.1016/j.jclepro.2006.08.003.

Braungart, M., P. Bondesen, A. Kälin & B. Gabler, (2008). Specific Public Goods for Economic Development: With a Focus on Environment, British Standards Institution (eds), Public Goods for Economic Development. Compendium of Background papers, United Nations Industrial Development Organisation, Vienna).

Brändström, J. & Eriksson, O. (2022). How circular is a value chain? Proposing a Material Efficiency Metric to evaluate business models. Journal of Cleaner Production, 342. 130973.

Bocken, N. M. P., de Pauw, I., Bakker, C. & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5): 308-320. 10.1080/21681015.2016.1172124

Buterin, V. (2013). Ethereum White Paper

Čapko, D., Vukmirović, S. & Nedić, N. (2022). State of the Art of Zero-Knowledge Proofs in Blockchain. 2022 30th Telecommunications Forum (TELFOR). pp. 1-4

Carminati, B., Rondanini, C. & Ferrari, E. (2018). Confidential Business Process Execution on Blockchain. In: 2018 IEEE International Conference on Web Services (ICWS). pp. 58–65. 10.1109/ICWS.2018.00015

Çetin S., Gruis V. & Straub Ad. (2022). Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations, Resources, Conservation & Recycling Advances, Volume 15, 2022, 200110, ISSN 2667-3789, 10.1016/j.rcradv.2022.200110.

Charef, R. (2022). Supporting construction stakeholders with the circular economy: A trans-scaler framework to under-stand the holistic approach. Cleaner Engineering and Technology, 8. 100454

Copeland, S. & Bilec, M. (2020). Buildings as material banks using RFID and building information modeling in a circular economy. Procedia CIRP, 90, 143-147. 10.1016/j.procir.2020.02.122

Concular. https://concular.de [accsess date 16.01.2024]

DGNB. https://www.dgnb.de/en [access 13.4.2024]

Di Giuda, G. M., Pattini, G., Seghezzi, E., Schievano, M., & Paleari, F. (2020). The Construction Contract Execution Through the Integration of Blockchain Technology. In: Digital Transformation of the Design, Construction and Management Processes of the Built Environment (pp. 27-36). Cham: Springer International Publishing.

Dodampegama, S., Hou, L., Asadi, E., Zhang, G. & Setunge, S. (2024). Revolutionizing construction and demolition waste sorting: Insights from artificial intelligence and robotic applications. *Resources, Conservation and Recycling,* 202: 107375. https://doi.org/10.1016/j.resconrec.2023.107375

EN 15978:2011 Sustainability of construction works – Assessment of environment performance of buildings Calculation method.

EMF (2013).Towards the Circular Economy 1: Economic and business rationale for an accelerated transition. Retrieved, Ellen MacArthur Foundation

EU Taxonomy (2024) https://ec.europa.eu/sustainable-finance-taxonomy/home [accessed 14.4.2024]

Figge, F., Thorpe, A. & Gutberlet, M. Definitions of the Circular Economy - Circularity Matters (2023). Ecological Economics, Vol. 208, 2023, Available at SSRN: https://ssrn.com/abstract=4398717

García-Bañuelos, L., Ponomarev, A., Dumas, M. & Weber, I. (2017). Optimized Execution of Business Processes on Blockchain. In: Business Process Management. pp. 130–146. Lecture Notes in Computer Science, Springer International Publishing. 10.1007/978-3-319-65000-5_8

Gervasio Dos Santos, H. & Dimova, S. (2018). Environmental benchmarks for buildings. *EFIResources: Resource Efficient Construction towards Sustainable Design*. Ispra: European Commission. doi:10.2760/073513

Goldreich, O., & Oren, Y. (1994). Definitions and properties of zero-knowledge proof systems. Journal of Cryptology, 7(1), 1-32.

Heisl, F. & Rau-Oberhuber, S. (2020). Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. Journal of Cleaner Production, 243. 118482.

Kamble, S. S., Gunasekaran, A. & Gawankar, S. A. (2018). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Safety and Environmental Protection,* 117: 408-425. 10.1016/j.psep.2018.05.009

Kirchherr, J., Reike, D. & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Re-sources, Conservation and Recycling, 127. 221-232.

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J. & Hartley, K. (2023). Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. *Resources, Conservation and Recycling,*194:107001.10.1016/j.resconrec.2023.107001

Khosrowshahi F. (2017). Building Infromation Modelling (BIM) a Paradigm Shift in Construction, Building information modelling building performance, design and smart construction. Springer, 47 ff

Korhonen, J., Honkasalo, A. & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations, Ecological Economics, Volume 143, Pages 37-46, ISSN 0921-8009.10.1016/j.ecolecon.2017.06.041.

Kovacic, I., Honic, M. & Sreckovic, M. (2020). Digital Platform for Circular Economy in AEC Industry, Engineering Project Organization Journal (October 2020) Volume 9

López-Pintado, O., García-Bañuelos, L., Dumas, M., Weber, I., & Ponomarev, A. (2019) Caterpillar: A business process execution engine on the Ethereum blockchain 49(7), 1162–1193. 10.1002/spe.2702

Marangone, E., Di Ciccio, C. & Weber, I. (2022). Fine-Grained Data Access Control for Collaborative Process Execution on Blockchain. In: Business Process Management: Blockchain, Robotic Process Automation, and Central and Eastern Europe Forum. BPM 2022. Lecture Notes in Business Information Processing, vol 459. 10.1007/978-3-031-16168-1_4

McDonough, W. & Braungart M. (2002). Cradle to Cradle: Remaking the Way We Make Things, North Point Press, New York, NY

Meralli, S. (2020). Privacy-preserving analytics for the securitization market: a zero-knowledge distributed ledger technology application, Financial Innovation 6 (7). 10.1186/s40854-020-0172-y

Nakamoto, S. (2008). Bitcoin: a peer-to-peer electronic cash system

ÖNORM B 3151:2022. Dismantling of buildings as a standard method for demolition. Wien: Austrian Standards International

Pagoropoulos, A., Pigosso, D. C. A. & McAloone, T. C. (2017). The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Procedia CIRP,* 64: 19-24. 10.1016/j.procir.2017.02.047

Papamichael, I., Voukkali, I., Loizia, P. & Zorpas, A. A. (2023). Construction and demolition waste framework of circular economy: A mini review. *Waste Management & Research,* 41(12): 1728-1740. 10.1177/0734242x231190804

Partala, J., Nguyen, T. H. & Pirttikangas, S. (2020). Non-Interactive Zero-Knowledge for Blockchain: A Survey, IEEE Access, vol. 8, pp. 227945–227961. 10.1109/ACCESS.2020.3046025

Rangelov, M., Dylla, H., Mukherjee, A. & Sivaneswaran, N. (2021). Use of environmental product declarations (EPDs) of pavement materials in the United States of America (U.S.A.) to ensure environmental impact reductions. Journal of Cleaner Production, 283, 124619. 10.1016/j.jclepro.2020.124619

RRReMaker https://www.rrremaker.com/ [Accessed 14.01.2024]

Scott, D. J., Broyd, T. & Ma, L. (2021). Exploratory literature review of blockchain in the construction industry. Automation in Construction, 132, 103914. 10.1016/j.autcon.2021.103914

Shojaei, A. (2019). Exploring applications of blockchain technology in the construction industry, in: 10th International Structural Engineering and Construction Conference (ISEC), ISEC Press, University of Illinois at Chicago. 10.14455/isec.res.2019.78.

Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H. & Wang, J. (2021). Enabling a circular economy in the built environment sector through blockchain technology. Journal of Cleaner Production, 294, 126352. 10.1016/j.jclepro.2021.126352

Stahel, W. R. (1982). The product life factor. An Inquiry into the Nature of Sustainable Societies: The Role of the Private Sector (Series: 1982 Mitchell Prize Papers), NARC: 74-96.

Stahel, W. R. (1994). The utilization focused service economy: Resource efficiency," in B. R. Allenby and D. J. Richards (eds), The Greening of Industrial Ecosystems, National Academy Press, Washington, DC, 178–190

Stahel, W. R. (2010). The Performance Economy, Palgrave Macmillan Hampshire, Hampshire UK

Szabo, N. (1997). Formalizing and securing relationships on public networks, First Monday

Tomaz, A. E. B., Nascimento, J. C. D., Hafid, A. S. & Souza, J. N. D. (2020). Preserving Privacy in Mobile Health Systems Using Non-Interactive Zero-Knowledge Proof and Blockchain. IEEE Access, 8: 204441-204458. 10.1109/ACCESS.2020.3036811

Veit, D., Clemons, E., Benlian, A., Buxmann, P., Hess, T., Kundisch, D., Leimeister, J. M., Loos, P. & Spann, M. (2014). Geschäftsmodelle - Eine Forschungsagenda für die Wirtschaftsinformatik. In: WIRTSCHAFTSINFORMATIK - Research Notes, Number: 1, p.55-64

Weber, I., Xu, X., Riveret, R., Governatori, G., Ponomarev, A. & Mendling, J. (2016). Untrusted Business Process Monitoring and Execution Using Blockchain. In: Business Process Management, vol. 9850, pp. 329–347. Springer International Publishing. 10.1007/978-3-319-45348-4_19

Wüst, K. & Gervais, A. (2018). Do you need a blockchain?, 2018 Crypto Valley Conference on Blockchain Technology (CVCBT).

Zhang, J., Bhuiyan, M., Zhang, G. & Sandanayake, M. (2024). Life cycle assessment of kerbside waste material for an open-looped and closed-loop production– towards circular economy designs, Journal of Cleaner Production, Volume 434, 139991, ISSN 0959-6526. 10.1016/j.jclepro.2023.139991.