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Tracking Material Reuse across Construction Supply Chains

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***Abstract*—Material reuse and recycling plays a key role in reducing carbon emissions in the architecture and construction sector. A "Material Passport" (MP) is a record describing how a material is used throughout its lifetime, from genesis to termination, recording operations carried out on the material. The granularity of information recorded in a MP can vary, however ensuring that this provenance trail remains immutable is a key requirement. The benefits of using a MP, operations carried out on a MP, and recording of transactions within a distributed Blockchain (parachain) is described. A scenario is used to illustrate how the proposed approach can be used in practice.**

***Index Terms*—Parachains, Material Passports, Material Reuse**

1. Introduction

The construction industry contributes significantly to worldwide greenhouse gas emissions, accounting for 39% of global greenhouse gas (GHG) emissions [1] and responsible for utilizing approximately 32% of extracted natural resources globally [2]. Construction supply chains are specifically mentioned as a major domain for action in the European Green Deal [3], a set of policy initiatives by the European Commission to make the European Union carbon neutral by 2050.

One of the key issues in decreasing the environmental impact of the building sector is to promote circularity in supply chains by increasing material reuse. However, without reliable tracking systems in place, this is challenging to accomplish. Without tracking, it is difficult to determine the origin, destination, and state of the construction materials or products. Due to this, it is challenging to guarantee the safe and effective reuse of resources.

The Ellen MacArthur Foundation [4], a non-profit, advocates for the circular economy. The foundation created the "material passport" concept which promotes product traceability in a circular supply chain. A material passport (MP) is a record of a product's path from raw material extraction through to its end of life stages. It facilitates the timely dissemination of information across the supply chain. The MP contains details about a product's composition, environmental impact and location. The MP concept has seen favourable uptake within numerous industry projects including Buildings As Material Banks (BAMB) [5], ORMS [6] and Madaster [7]. An MP can be used to track a material throughout the construction supply chain and identify the origin of a material. Additional information on construction materials could also influence the building construction phases to be more effective and less wasteful. Materials that reach the end of their useful life could be properly disposed of using information in their MP.

Despite the benefits and successes of using MP, limitations still exist that need to be addressed to realise more sustainability in the construction sector. Firstly, there is currently no unified approach or standard to generating MPs. The lack of standards leads to differing terminologies or processes used and represented in MPs thereby reducing their usefulness for other construction partners. Secondly, construction supply chains compose of multiple stakeholders which handle a product at various stages of its lifecycle. This leads to challenges pertaining to keeping the material passport up to date throughout a product's lifecycle. Thirdly, there are confidentiality challenges pertaining to the sharing of business information in materials passports. We describe the use of MPs whiles mitigating these limitations.

Blockchain is a key enabler for the requirements identified above, and can be used to support circularity in supply chains. The rest of this paper is divided into various sections. The next section gives more background information on the tools and techniques employed in the proposed model as well as motivation for the work. Subsequently, some work scenarios are presented prior to the implementation strategy. The paper concludes with an evaluation of the model and summary of the project including suggestions for future work.

2. Background and Motivation

In this work, an MP and its supporting ecosystem was designed and implemented to reflect key aspects of circular supply chains. These include material use transparency and traceability, data integrity and autonomy, stakeholder interoperability and collaboration, circularity evaluation, governance and compliance, scalability and performance. The following key questions were considered:

Q1: Does the approach support the transparency and traceability of materials and products throughout the supply chain, and provide the current state of a material in the supply chain?

Q2: Can this approach support data autonomy and integrity for the various stakeholders in the supply chain?

Q3: How can the MP and its associated infrastructure enable the integration of material data with other relevant information systems within the supply chain ecosystem, and support scalability as the number of actors in the supply chain increase?

Q4: Can the approach support transparency about an organisation's eco-footprint e.g. CO_2-accounting and percentage of reused material versus new materials?

Q5: How does the model facilitate compliance with relevant regulatory requirements and the Royal Institute of Building Architects (RIBA) Plan of Work?

Based on these questions, our design and implementation aims to achieve the following design goals (i) **Verifiability** Supply chain information can be stored on a standard database, but this does not guarantee the security of the data by default. A Blockchain enables verifiability of information without a trusted third party, supporting trust among the participating entities by ensuring the integrity of the product on-chain and that the product comes from the specified entity. (ii) **Privacy:** In a public blockchain, participating entities can see the information stored on the blocks. To support privacy, organisations can use locally managed private blockchains, requiring blockchains to communicate with each other for participants involved in a construction project. This necessitates interoperability between the blockchains. The participating entities should be able to manage their private data and blockchains while sharing the information they want other entities to access. Our architecture uses *Parachains* to achieve this goal. (iii) **Minimum on-chain information:** A specific product can have many attributes and storing all on a blockchain will not scale. One approach is to store information off-chain and maintain a reference on the blockchain. Off-chain information must ensure data availability, overcome single-point failure and data manipulations. Our architecture uses IPFS to achieve this objective. (iv) **Provenance:** A product may undergo changes of ownership in different stages of its life cycle. It is important to have the complete history of a product to understand its duration of use and assess its quality. We have developed provenance tracking to trace back the product to its origin on the blockchain.

3. Wood Reuse Scenarios

A simplified wood construction supply chain scenario is used to describe the application workflow, as depicted in Figure 1. This scenario encompasses seven distinct entities, each representing different companies within a supply chain. The initial stage includes the manufacturer, responsible for obtaining raw materials and produce the initial "product". This stage also involves the creation of a material passport (MP). These manufactured goods are sent to end users within the construction domain via intermediate warehouses for temporary product storage. Concurrently, logistics firms facilitate the seamless exchange of goods between these various entities.

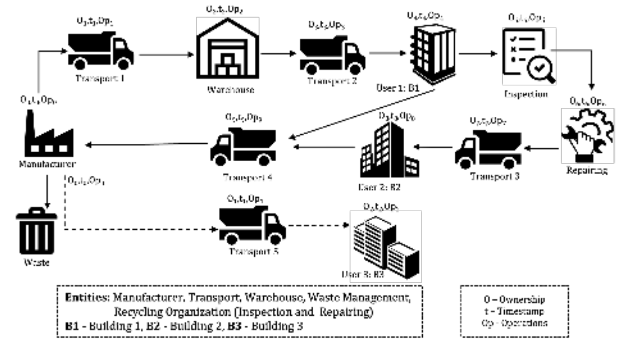

Figure 1: A Wood Reuse & Recycling Scenario in Construction Supply Chain

Within the framework of a reuse loop, products that have fulfilled their intended purpose are subjected to meticulous scrutiny and subsequently redirected to new end users following requisite refurbishments, in adherence to product specific reuse standards. Conversely, products that fall short during the inspection phase are reclaimed by the manufacturer for recycling. The combination of ownership, timestamps and operational attributes is adopted to delineate the MP's evolving status. Ownership serves to designate the current possessor of a specific product, generating a comprehensive historical record within the MP. The timestamp assumes the role of a unique identifier, instrumental in distinguishing individual transactions.

4. Implementation

The implementation of the scenario in section 3 is realised as illustrated in figure 2, using Polkadot as the blockchain platform, Material Passports (MP) and IPFS as decentralised storage. Polkadot is a blockchain network and protocol created by the Web3 Foundation and Parity Technologies to promote blockchain interoperability. Polkadot network uses a sharding technique to divide transactional data into smaller partitions to process transactions simultaneously. The individual blockchain shards are called *Parachains*, which are Layer-1 blockchains connected via a *Relay chain* to create a consolidated network. The *Relay chain* serves as the base layer of the Polkadot network. It facilitates communication among *Parachains*, contributing to decentralisation of the blockchain network. All chains in the network can process transactions simultaneously, and only a selection of transaction outcomes through the *Relay chain* may be publicised to the Polkadot network. *Parachains* can operate simultaneously and can be customised by their owners. They can be tailored for specific applications and include their own set of programming logic.The *Validator* nodes maintain the *Relay chain* and are responsible for creating and verifying new blocks. Each *Parachain* has a specific set of *Validator* nodes assigned to it for generating new blocks on the *Relay chain*. Nodes known as *Collators*

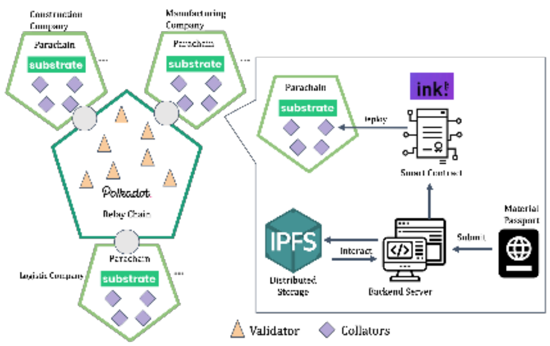

Figure 2: Multilayer Blockchain Architecture

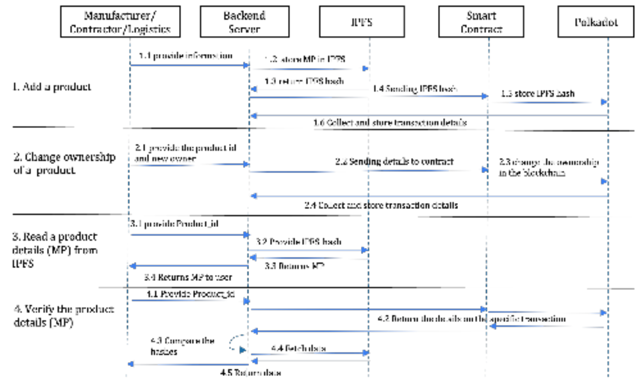

Figure 3: Sequence Diagram

have the task of gathering block states and sending them to the *Validator* on the *Relay chain*. They are responsible for collecting transactions from *Parachains* and submitting them to the *Relay chain* via the *Validator* [8].

The architecture has three entities mentioned in our use case: Manufacturer, Logistics and Construction company. Each entity maintains its own *Parachain*. The manufacturer generates the MP of the product and pushes the information to the *Relay chain*. The Smart Contract assigns the initial ownership to the manufacturer, and only the current owner can transfer the ownership of the product to a new entity. Smart Contracts realise validation processes to ensure the smooth implementation and automation of the architecture.

InterPlanetary File System (IPFS) is a network-based protocol used to create a decentralised and efficient method for storing and sharing files online, different from traditional centralised servers and web hosting systems. IPFS is composed of four key components that ensure high performance, security and throughput. These include the Distributed Hash Table (DHT), Self-Certifying File Systems (SFS), BitSwap protocol and Merkle DAG structure [9]. IPFS is not a distributed database but a distributed file system. MP may contain a variety of different data types: text-based information on the product, CAD diagrams of building schematics, etc. If all the information were to be stored on the blockchain, then there would not be any need for a decentralised storage. Information on IPFS is immutable and storing the content identifier (CID) of IPFS on the blockchain, adds an extra layer of security. Any change in the data generates an entirely new CID. Our architecture stores the MP within the IPFS, and its reference (CID) is stored on the blockchain. Storing MP on IPFS has two benefits: (i) ensures data immutability as it generates a new CID; (ii) overcomes single-point failure of centralised off-chain storage due to its distributed nature.

4.1. Practical deployment

The architecture is implemented on Polkadot 0.9.40 and Smart Contracts realised using *Ink* version 4. The front end, using *Polkadot.js* [10], communicates to the Smart Contract and performs the transactions on the chain. All participating entities are required to maintain both a *Parachain* node and a MongoDB database. The communication between these entities and the backend occurs through their respective MongoDB databases, and the Smart Contract deployed on the chain. Within the backend architecture, a central master MongoDB database keeps an index of all entities engaged in the supply chain. The backend orchestrates the interaction with the Smart Contract during transactions, ensuring that a corresponding entry is also made in the requesting entity's database. Each individual entity's database improves local data retrieval and minimises transaction fees associated with frequent queries. In case of a database failure, all essential data remains recoverable from the blockchain. Whenever a user seeks resources from the supply chain via the backend, a crucial authentication step comes into play. This authentication process takes place through the Smart Contract, which maintains a registry of user permissions linked to their respective wallet addresses. Once authentication is successfully established, the Smart Contract issues an access token, allowing the backend to access the database of the requested entity.

As not all information is stored on the blockchain and IPFS is not a database to query information, a backend server in our system maintain a database of the information to enable more efficient querying of data. Using backend servers does not pose a single-point failure in our architecture as long as the *product_id* is available, which is the mapping key on the blockchain. Data will be accessible if we have the *product_id*, to fetch information from the blockchain and get the product details from IPFS. Information retrieved from both blockchain and IPFS can verify the authenticity of a product and blockchain can provide the provenance.

Figure 3 illustrates this processes. There are four basic operations: adding a product to the chain, changing the ownership of the product temporarily or permanently, retrieving product details (MP), and verifying the details of the product on the chain. Only the manufacturers can add a product to the chain, which acts as the first product reference on the chain. Only the current owner of the product can transfer it to another actor. MP information can be accessed both with and without verification. When the IPFS hash is retrieved from the backend server, it does not involve the blockchain.

TABLE 1: Smart Contract Functions

Functions	Input	Output	Gas Fee*
grant_roles	userID, Role	Success/fail	0.11363819
revoke_roles	userID	Success/fail	0.11363819
check_roles	userID	Role the user	No
get_participants	—–	List of participants	No
add_product	product_id, userID, MP_hash	Transaction details	0.11363829
transfer_product	product_id, userID, previous transaction details	Transaction details	0.11363829
get_MP	product_id	MP	No
get_owner	product_id	userID	No
get_pro_details	product_id	Product info	No
get_pro_history	product_id	Previous owners list	No

*Gas estimates only include partial fees. Full transaction fees can only be calculated in the production environment.

However to support verification, the IPFS hash has to be retrieve from the chain.

A Smart Contract uses multiple data structures and background checks to manage transactions efficiently. It uses role-based access control (RABC) to identify the entities. During the time of the deployment of the Smart Contract, two users are appointed as admin who have the role of appointing other users with their roles. The roles are defined as Enums and use a tuple mapping to map the roles with users. There are four admins-specific functions: *grant_roles*, *revoke_roles*,*check_roles* and *get_participants*. The function *add_product* is reserved for the manufacturers only. The other functions are accessible to all the other entities.

5. Evaluation

As described in section 4, functions that involve write transactions require gas fees, while reading does not require a gas fee. Most often, the inputs are *userID* or the *product_id*. Table 1 shows the functions and their purposes. As described in the final column of table 1, each function exacts a consumption of 0.11363819 DOT per transaction within a localized Polkadot development environment. When a product is added to the chain, what goes to the chain is its MP reference which is a 46-character string from IPFS, and it is stored as a hash datatype of Ink. In the situation of transferring a product, we store the details of the transactions (transaction and block hashes). In a single-layer blockchain, the details of a transaction can be retrieved by transaction hash, while Polkadot requires both [11]. Having the transaction details embedded in the Smart Contract enables the participants of the network to trace backwards on the ownership information independently.

6. Summary and Conclusion

A multi-blockchain (referred to as a *Parachain*) based system, implemented using Polkatdot and IPFS, is described to support product recycling in the construction sector. Each organisation involved in the supply chain for a product can maintain a local blockchain, record local transactions and only make visible a subset of these based on pre-defined consensus between project partners. This enables scaleup and autonomy, enabling supply chains to be extended without requiring a centralised blockchain platform. Using a scenario, we describe how the proposed approach can be used in practice, involving various actors in the supply chain – manufacturer, logistics companies, warehouse and storage companies and consumers. A key component to realise this circular supply chain is a material passport (MP) – a trail of all operations that were carried out on a product during its lifetime. We propose the use of a *Parachain* to manage a MP, providing trust to all actors in a supply chain on the authenticity of information it contains. Our proposed approach can be re-used in a number of other use cases, including reuse of plastics, garments in the fashion sector and vehicle parts.

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