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Overcoming Information Asymmetry in the Plastics Value Chain with Digital Product Passports

How decentralised identifiers and verifiable credentials can enable a circular economy for plastics

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1 Introduction

Plastics currently are among the most ambiguous and most debated materials. They are versatile, easy to produce and manufacture, and adaptable to many utilisations. However, the materials' ubiquity has turned it into a major problem to the environment. Hence, political and social pressure to overcome these problems has emerged and becomes increasingly powerful. For example, the European Union's (EU) Circular Economy Action Plan and the Single Use Plastics Directive are embodiments of this fact.

Due to their advantages, plastics are often cheap and important enablers of other processes, for example in packaging. With regard to plastics, it is greenhouse gas emissions and plastics waste combined with the short life span especially of plastics packaging that create the predominant environmental problems. Both issues can be countered by the implementation of a circular plastics economy.[1]

Meanwhile, many players in the supply chain, among them plastics producers, manufacturers, recyclers, retailers, research, etc. seek for solutions to create a functioning circular plastics economy. A resource efficient circular plastics economy can be characterised as keeping plastics products and materials as long in the economic cycle as possible i.e., as long as this provides an environmental advantage. To maintain its value, the material should always be brought to an application level that retains as many of its qualities as possible. This implies avoiding "downcycling" or cascadic use wherever possible.

However, this is not an easy task. One of the challenges faced in this endeavor is information asymmetry and intransparency in the market for recycled plastics (recyclates). There is a persisting knowledge gap between plastic recyclers and producers of plastic products (manufacturers) which leads to underperforming markets and lower amounts of high value recycling. As a result, many plastics are either burned or landfilled instead of recycled.

Overcoming this information asymmetry could create new markets and applications for plastics recyclate in a circular economy. The obvious prerequisite is to create, transform and transport the information required. A task that could be enabled by emerging digital technologies that help improving identification and traceability of plastics material, e.g., providing evidence on the specifications and qualities of a defined plastics batch.

This paper analyses the potential of novel digital information carriers to improve reliable provision of information along the plastics supply chain. We investigate the possible contribution of product passports implemented as decentralised identifiers and verifiable credentials to overcome information deficits and information asymmetry in the circular plastics economy. We test how these instruments could close the information gap by making information flows consistent and reliable along the

[1] Notwithstanding the fact, that with regard to Greenhouse Gas Emissions the change towards renewable energy is another mandatory step.

supply chain. This way, the quality and origin of recycled plastic material can be made traceable and verifiable. Such passports may therefore have the potential to increase trust and transparency along the entire supply chain as well as to create new forms of recycling.

The paper proceeds as follows: Chapter 2 discusses the issue of information deficits and its implications for the establishment of a circular economy for plastics. Chapter 3 introduces suitable strategies to overcome those deficits. The fourth chapter details how these strategies can be enabled by establishing verifiable product information through decentralised identifiers and verifiable credentials. Chapter 5 illustrate how decentralised identifiers and verifiable credentials for plastic products can be applied to improve plastics recycling. The paper's findings and future work are discussed in Chapter 6.

2 The current Situation of the Plastics Value Chain

Until now, a circular economy for plastics only partly exists. Especially so, since the high variety of plastics and high market intransparency make recycling extremely demanding. It is hence not surprising, that the use of secondary plastics materials in European plastics manufacturing has remained relatively stable on a low level of around 13% Conversio 2020), despite of intensive measures undertaken to create large scale plastics recycling over the past three decades. At the same time, the amount of plastics waste constantly rises and the demand and utilisation of plastics is expected to continue to rise in the foreseeable future (Enkvist et al. 2018). In consequence, it is expected that plastics waste and plastic-related pollution rise as well. The creation of transparent and reliable markets for plastics recyclate is thus of highest importance. However, high value recycling where e.g., plastics recyclates are being reemployed into their former use comes with high technological demands to achieve purity of type (and often color). In many applications even small contaminations with other types of plastic may render a batch less recyclable since quality is degraded. In some cases, recyclate even becomes unusable and therefore worthless.

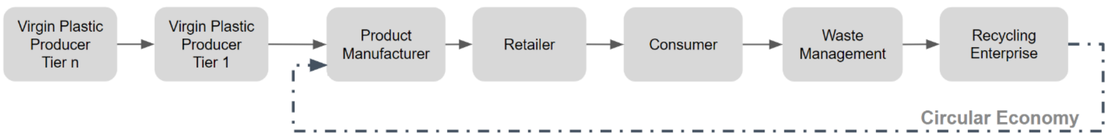

Figure 1: The stylised plastics value chain. Own representation.

Figure 1 shows a stylised depiction of the plastics value chain, including the recycling process. At present, means to easily prove quality and composition of recyclate are rare. Recyclate markets are thus distorted. Reliable information on which material can be procured in which purity at what scale in which point of time are often hard or impossible to obtain, especially when large amounts of recyclate are required for a longer timeframe to secure ongoing and future production in mass markets. The use of plastics recyclate is therefore most often expensive when compared to primary material, which due to the production processes can be expected to be pure without any need for further quality control on the side of the plastics manufacturer. These problems have led actors in the plastics supply chain to look for alternative solutions for creating reliable flows of high-quality plastics recyclate.

One solution has been the integration of the whole circular flow within one company or group. In effect, such a solution implies using only plastics produced and recycled within the own company. In this approach the (almost) complete control and transparency over plastics materials and therefore the minimisation of insecurity is created by the construction of a closed system. However, this comes with the disadvantage, that all other participants are exempted from the use of these specific plastics for the foreseeable future.

Another approach is the reduction of insecurity by utilising recyclates that stem from less risky and complex sources. This especially refers to secondary materials produced from industrial plastics waste. In general, such waste streams are cleaner and purer in type. However, they only cover a small fraction of the plastics waste produced each year, and therefore do not tackle the bulk of environmental problems at hand. The much larger amounts of post-consumer plastic waste cannot be addressed in this way. This leads to inferior applications of such plastics, such as use as fuel surrogate in the production of cement and other materials, or to direct incineration. In many countries, landfilling of plastics waste is also still practiced. In effect, material of high potential value is lost forever.

Another successful way has been the introduction of deposit schemes, e.g., for PET-bottles in Germany. Such systems lead to very clean material streams as they only accept very distinct products and directly incentivize circularity. However, they are also complex and need to be well-managed. Such schemes for the large variety of existing plastics would be very demanding. However, they are complex to establish and may not be suitable for each product, e.g., when plastics-made components are used for assembly in more complex and long-living products.

Currently, all these facts make plastics recycling an expensive and cumbersome endeavor for most plastics manufacturers that are willing to use recyclate, since missing information leads to high search and transaction costs as the right material must be found and meticulously tested in laboratories, before it can be used in production processes. Evidently, total measurement costs even grow with the amount of recyclate employed, since more testing is required either on the side of the supplier (most often a recycler) to demonstrate and assure quality or on the side of the user for the same reasons. In both cases, the costs of the recyclate increases and the attractiveness of recycling from a purely economic point of view decreases. Such costly information deficits regarding secondary plastics material currently concern almost every aspect of the market. In the past, especially insecurities and bad experience regarding the true quality of plastics recyclate have created a lack of trust between the different actors in the plastics cycle and strong reservations on the side of potential customers, which further compromises plastics recycling.

3 An Interpretation from new institutional Economics: Strategies to overcome the Information Asymmetry

As has been shown, information deficits and asymmetries are a core problem of establishing functioning plastics recycling on a larger scale than today (Wilts/Berg 2018). In most instances, the risks associated with information deficits and information asymmetry are attributed to utility-optimising behavior by the party with superior information. They are described in the form of a hidden agenda, a moral hazard etc. and can lead to adverse selection on the side of the buyer. The situation of the plastics supply chain as depicted above shows just this picture. Lack of information and unevenly distributed information leads to insecurities, mistakes and hence, distrust, which eventually creates dysfunctional markets.

Transaction costs result from these risks caused by incomplete information and information asymmetry (Williamson, 1985). They result inter alia from the need to determine the value of a good or service in several dimensions such as measurement of quality (e.g., Barzel 1982) and from the need to properly enforce contracts (North, 1993).

Some classical norm strategies have been devised to overcome situations of incomplete information. Some of these are already in place in the plastics recycling markets:

1 | Integration: The integration of e.g., a supplier into a company's own organisation reduces risks by introducing direct dependency and control (Coase 1937). As has been pointed out above, this approach has already been put into practice in the plastics industry in some instances.

2 | Increasing the basis of information / signaling: The selling party provides clear references or documentation e.g., on the quality of a material by supplying a buyer with results of laboratory tests for a certain batch of recyclate. Such a signal creates more trust and transparency but must be seen more as a hint rather than a complete mitigation action.

3 | Contractual solutions / warranties: Provision of warranties by the supplier mitigates the buyer's risk and shifts it to the seller. This creates both more trust and stability in a market relationship, as the supplier is incentivised to additional care regarding the products he or she provides. However, it may be difficult to proof deficiencies in a certain batch and hence enforce a warranty after the manufacturing process. Moreover, since warranties only become effective once a damage is done, they are affiliated with high potential costs in terms of money and time and can also result in losses of material and therefore less resource efficiency.

4 | Monitoring: In this approach, the buyer is entitled to surveil the production process to achieve transparency. However, depending on the monitoring process established it too can be costly and difficult to maintain. Especially so, when IP rights and know-how protection is involved.

Increasing effort to perform transactions and additional contractual complexity can thus lead to much higher transaction costs. Finding less costly ways to lower information asymmetries, to overcome the information deficits and to provide secure information would be a way forward to more functional markets.

Studies have shown that provision of data and use of digital instruments can improve circular economy practices. E.g., Kristofferson et al. (2020) explained how accumulation and analysis of data can enable resource efficient circular instruments. We argue that the same can be true for the compensation of transformation deficits and the reduction of transaction costs (see also Wilts/Berg 2018). Even today, most production steps and transactions are digitally documented but the data is not used for the circular economy. In terms of plastics recycling, it would be required to collect and share the following data:

- pureness of type,
- technical specifications of the recyclate (according to DIN SPEC 91446 these concern the rheological, mechanical and thermal properties) ideally measured and documented already in its production process,
- additives,
- color,
- availability of the recyclate supply (e.g., how much and when it is supplied),
- further qualitative aspects and certificates (e.g., if the recyclate conforms to food grade standards),
- results of laboratory tests (which laboratory, when tested, standards used, etc.).

Such data can then effectively compensate or eliminate information deficits and reduce transaction costs. It improves the transparency of the production process and creates new potential for the product and market design. Most of all, it can establish trust in a trustless web environment, where it can enable new markets and applications for recyclate and establish new market relations where partners do not know each other. One prerequisite however remains: The transaction costs for the documentation and provision of data must effectively lower the price of recyclate, as ceteris paribus no markets will be generated if the recyclate prices are still much higher than those for primary materials. In the following chapters we show how these processes can be enabled and the requirements met with the help of decentralised identifiers and verifiable credentials.

4 Solution Design for Digital Product Information to overcome Information Asymmetry in the Plastics Life Cycle

4.1 Trust and trustless systems in a digital economy

An identity represents a specific combination of characteristics and roles of an object (physical, contextual, logical object) (Tsolkas & Schmidt 2017). Digital identities therefore are sets of attributes stored or processed in one or more IT (information technology) systems that are assigned to a unique identifier. Identities for products or product groups are often referred to as product or material passports and in some cases also as digital twin. The use case examined in this paper describes a new way of establishing a unique digital identity for a consumer product from the perspective of recycling. In a circular economy, information about the composition of the materials used and, in some cases, the origin of materials is required as part of the product passport.

The current, investigated approaches for the implementation of product passports are inter alia the battery passport regulated by the European Commission (European Commission 2020), the circularity.ID of the circular.fashion UG[2], the CircularID Protocol by the EON group[3], and the Product Circularity Data Sheet (PCDS)[4] as part of the Luxembourg Circularity Dataset Standardization Initiative. They complement further standardisation of data schemes for recycling materials for instance GreenBlue's Recycled Material Standard Framework (RMS)[5]. Moreover, BASF[6] and Circularise[7] have started similar initiatives.

In research, digital identities appear for various use cases to build an efficient and competitive, secure, and trustworthy data infrastructure, such as required by the European Commission's data strategy[8] and Gaia-X. EU's draft towards a more sustainable single market for business and consumers for instance notes: "A digital strategy for a sustainable market Welcomes the announcement of a common European data space for smart circular applications and the ambition of the Commission to develop a digital 'product passport' to improve traceability and access to information on the conditions of production of a product, durability, composition, reuse, repair, dismantling possibilities and end-of-life handling, taking into account the proportionality principle and costs for businesses and paying special attention to the needs of SMEs, micro-enterprises and the self-employed; calls for these tools to be developed in close

[2] circularity.ID by circular.fashion https://circularity.id/ and https://github.com/circularfashion/cf-circularity-id-standard

[3] CircularID Protocol https://www.eongroup.co/download-circularid-protocol

[4] Product Circularity Data Sheet https://pcds.lu/pcds-system/ and ISO/AWI 59040 Circular Economy — Product Circularity Data Sheet https://www.iso.org/standard/82339.html (part of ISO/TC 323 Circular economy)

[5] Recycled Material Standard https://www.rmscertified.com/about/standard/

[6] https://www.basf.com/global/en/who-we-are/sustainability/we-value-people-and-treat-them-with-respect/starting-ventures/recichain.html

[7] https://www.circularise.com

[8] https://digital-strategy.ec.europa.eu/en/policies/strategy-data

cooperation with the industry and relevant stakeholders" (European Parliament 2020).

Since information in IT systems can be easily copied and changed from a technical point of view, creation of trust in such a digital identity is one primary research subject. In the following, this paper proposes a decentralised concept for exchanging verifiable product and material information between market participants. It proposes to use a decentralised public key infrastructure (dPKI), which allows to create digital identities for companies and products and to exchange trustful and digital product passport data among all players of the plastics industry. We will show how, with the suggested approach, all product information regarding origin, integrity and compliance can be verified, which creates trust along the entire supply chain.

In addition, we will show how decentralised, digital identities allow for interoperability between the various market participant roles and their diverse business software systems.

4.2 Design goals for an ecosystem that provides trusted electronic product information

Design goals[9] of a system that provides trusted electronic product information can be derived from initiatives about decentralised (personal) identities. We transfer those design goals to decentralised product identities, which shall be:

1 | **Controllable.** Data owners shall have direct control over their personal data (self-sovereign identity) and the material or product information they provide.

2 | **Decentral.** The system that issues product identities shall have no central component/intermediary to avoid the risks of a central, single point of failure or no central governance. Instead, the solution shall be decentralised to allow all market participants to add products and product information to the ecosystem.

3 | **Private.** The privacy of shared information must be guaranteed where needed, e.g., to protect business secrets. Legal requirements, especially around data protection, protection of property rights, and confidentiality according to business secrets need to be fulfilled.

4 | **Secure.** The product data provided must be correct. Its origin and integrity need to be verifiable, and the data needs to be stored safely from unauthorised access.

5 | **Discoverable.** All information about players, material and products needs to be discoverable for authorised parties. It must be possible to interact with the entities and owners of the data. For example, recyclate batch data needs to be clearly identifiable, so that a biunique identification can be made. Information shall travel with the material along the production process and shall be reusable in a consecutive recycling process.

[9] Design Goals, see https://www.w3.org/TR/2021/PR-did-core-20210803/ in combination for instance EU 849/2010, in Germany Umweltstatistikgesetz (UStatG), for export/import EC 1013/200 but also standards like ISO 14040 ff.

6 | **Interoperable.** The solution needs to be built on standards to allow the largest possible degree of interoperability. Data schemas that describe the product need to be standardized, i.e., technical encoding and values and their semantics must be jointly understood and agreed on by all market participants. Technical updates that come with the extension and updating of underlying standards must also be possible.

7 | **Portable.** The digital identities must remain permanent and must be usable in various systems and networks, thus implement the openness to various digital ecosystems.

8 | **Simple.** The solution must be simple and easy to access for market players.

9 | **Extensible.** The solution needs to easily extensible for additional market players and use cases (e.g., for calculating the carbon footprint of plastic virgin material) and ready for a broader, international use. Data from different sources (e.g., databases like Product Environmental Footprint [10] or Substances of Concern in articles as such or in complex objects (Products)[11]) needs to be integrable.

4.3 Implementing an ecosystem for trusted electronic product information in the plastics life cycle

This chapter addresses how the design goals of chapter 4.2 are met, especially in the context of the Circular Economy.

4.3.1 Controllable

The term self-sovereign identities (SSI)[12] refers to a new value in various design goals compared to classic approaches. SSI follows the concept that an identity keeps and controls access to all information about itself. This approach is a counter initiative to the platform centric identity management by Facebook, Google, Amazon, etc. The term is most often used to describe the design goals for decentralised personal identities[13]. However, digital products have the same design goals and therefore SSI also drives the design for digital product passports with the goal to enable the Circular Economy. Using SSI in the product context refers to the self-sovereignty for the product data owner, i.e., the direct control over product information by the manufacturer. Each company in the value chain owns the sovereignty data of their production process. Another example is the licensee of the packaging materials (acc. to German packaging law 'Verpackungsgesetz' VerpackG that is based on directive 94/62/EC), usually the retailer of the product, who generates and thus fully controls data about the product packaging.

[10] Product Environmental Footprint (PEF) https://nexus.openlca.org/database/Environmental%20Footprints

[11] Substances of Concern In articles as such or in complex objects (Products) - SCIP https://echa.europa.eu/de/scip

[12] Christopher Allen, "The Path to Self Sovereign Identity", Coindesk, April 2016, https://www.coindesk.com/markets/2016/04/27/the-path-to-self-sovereign-identity/

[13] For example, Rebooting Web-of-Trust initiative https://www.weboftrust.info and Ehrlich, T., Richter, D., Meisel, M. & Anke, J., (2021). Self-Sovereign Identity als Grundlage für universell einsetzbare digitale Identitäten. HMD Praxis der Wirtschaftsinformatik: Vol. 58, No. 2. Springer. (S. 247-270). DOI: 10.1365/s40702-021-00711-5

4.3.2 Decentral

The underlying technologies for self-sovereign product data registries are Decentralised Identifiers (DIDs) and Verifiable Credentials (VCs)[14]. In our example in Section 4, every company in the supply chain and every product/material needs a unique DID. DIDs are not created centrally by one organisation but by the DID owner (also called subject) itself. Information that describe the company or the product DID further are issued by organisations or business partners in the form of electronically signed VCs. For example, a GS1 accredited company issues the verified manufacturer address to the manufacturer DID, or an auditor issues the ISO 9001 Quality Management (QM) and the IS0 14001 Environmental Management (EM) certificate to the company DID or the manufacturer issues the plastic raw material code to the product DID.
Decentralised Identifiers are often anchored with distributed ledger (DLT) technologies, such as the Ethereum protocol, to allow a decentral, trustworthy storage of the DID documents. DID documents describe the DID subject and most importantly contain the public key for electronic signature validation.

DID excurse and example: In our example in Section 4, the product-DID looks as follows:

```
did:ethr:spherity:testnet:0x828efeeaab06dd9541992b791d78e5d96cd35323
```

DIDs have the same syntax as URLs, which are described in the Uniform Resource Identifier Standard[15] once defined by Tim Berners-Lee et al. DIDs start with `did` defining the URI scheme, followed by the DID-Method `ethr` (defining that the used ledger is Ethereum) followed by the DID method specific identifier, here `spherity:testnet:0x828efeeaab06dd9541992b791d78e5d96cd35323`. The DID method describes how the DID document can be managed (e.g., created, found(resolved), updated or deleted). The beginning of the specific identifier points to the concrete ledger (here: `spherity:testnet`) where the DID document is hosted/can be retrieved (here an Ethereum test network operated by Spherity). Finally, the long number is the actual identifier. The combination of the DID Method, the concrete ledger and the identifier ensure that the DID is globally unique and can also be used outside the distributed ledger.

4.3.3 Private

With the above-mentioned verifiable credentials, the company, product, or material DIDs collect verifiable attributes about themselves which they can store in a so-called *wallet*. The more testimonies from trustworthy, verifiable issuers a DID has, the more trustworthy it gets. Only the DID subjects have control over their wallet. The

[14] Detailed description of the technology could be found in the W3C specification "Decentralized Identifiers (DIDs) v1.0 - Core architecture, data model, and representations" https://www.w3.org/TR/did-core/ , "Verifiable Credentials Data Model v1.1 - Expressing verifiable information on the Web" https://www.w3.org/TR/vc-data-model/ , "Use Cases and Requirements for Decentralized Identifiers - W3C Working Group Note 17 March 2021" https://www.w3.org/TR/did-use-cases/ , and "DID Specification Registries - The interoperability registry for Decentralized Identifiers" https://www.w3.org/TR/did-spec-registries/

[15] RFC 3986: Uniform Resource Identifier (URI): Generic Syntax https://datatracker.ietf.org/doc/html/rfc3986

wallet owners can decide which verifiable credentials they want to present to whom and thus have control over their privacy.

4.3.4 Interoperable & Extensible via Standardisation

Decentralised identifiers and verifiable credentials are standardised by the W3C. Everyone who implements those standards can participate at the decentralised ecosystem. The communication between wallets (e.g., to present or verify a VC) is standardised by the Decentralised Identity Foundation (DIF). The combination of the technology above allows for an interoperable and extensible technological basis for decentralised identities of people, organisations, and things and their digital twins.

4.3.5 Portable & Resolvable

In the supply chain the product identity needs to move with the product along the value chain. For portability, decentralised identifiers and verifiable credentials can be coded and represented as standard 2D codes (such as QR Codes). This helps to transfer DIDs and VCs from the digital to the physical world.

The product DID
`did:ethr:spherity:testnet:0x828efeeaab06dd9541992b791d78e5d96cd35323`
that we use in our example can be encoded into a 2D code. Figure 2 shows the respective encoding of the DID as a QR code. Using this code on product packaging can link the physical product to the digital product passport. It is also possible to use Concise Binary Object Representation based Serialization for Linked Data (CBOR-LD)[16] for the encoding and thus enlarge the information in the QR code and even make it verifiable. This technology is used for example in the W3C draft for vaccination credentials[17].

Figure 2: QR code linking to the digital Product Passport

[16] "CBOR-LD 1.0 - A CBOR-based Serialization for Linked Data" https://digitalbazaar.github.io/cbor-ld-spec/

[17] Vaccination Certificate Vocabulary v0.1 W3C 20 April 2021 https://w3c-ccg.github.io/vaccination-vocab/

To link back from the QR code to the digital product DID and its VCs an app needs to be built with the following logic: When the code is scanned by a QR code reader, such as a mobile device, the application decodes the DID. The DID then links (resolves) automatically to the DID document. In addition to the public key, the DID document includes service endpoints or other locations where the VCs of the product DIDs are stored. For example, if a DID is registered on the Ethereum main net, then its DID Document can refer to functionality and data outside the Ethereum mainnet via the service endpoints. Behind the service endpoints all product information is stored in decentralised databases in the form of verifiable credentials.

This is a different approach than the digital watermarks initiative Holy Grail 2.0[18] that invisibly puts recycling information directly on the packaging, which can then be read by recycling machines. While information in this case is directly available a drawback of this solution is that the information on the product is limited. Using an identifier that links to distributed data allows to attach limitless information about the product.

Also, propriety solutions are being discussed as a digital lookup mechanism for product information. However, current drawbacks of such approaches are limited accessibility only to customers, often a limited focus with regard to the information provided and potential limits concerning the forgeability depending on a given solution.

4.3.6 Secure

The access to the above-mentioned service endpoints can be regulated. That means that at this point an access control mechanism can be implemented to grant access to verifiable credentials (that store all information about the DIDs, here the product) only to authorised applications/users. This way it can be ensured that product information is secure and protected against unauthorised access.

4.3.7 Simple

The decentralisation of the above explained concept makes the implementation approach simpler than classical centralised systems, because the central storage of data, the central development of software and the heavy integrations between large industry players become obsolete.

[18] Digital Watermarks Initiative HolyGrail 2.0 https://www.digitalwatermarks.eu/ and https://www.gs1.eu/news/holy-grail-2-0-pioneering-digital-watermarks-for-smart-packaging-recycling-in-the-eu

5 Case Study: Decentral, Digital Identities and Verifiable Recycling Information for Plastic Products

This chapter describes a case study in the circular plastics economy. The first subchapter describes the use case and the general technical approach. The second subchapter shows the detailed steps to collect all information across the value chain based on DIDs and VCs. Subchapter 5.3. goes on a deeper technical level; it shows the examples of products passport attributes and code examples of DIDs and VCs

5.1 Case Study: Use case description and general approach

The following example describes the usage of decentralised identifiers for all market participants and physical products in the supply chain as well as the usage of verifiable credentials for the creation of a verifiable product passport. The use case focuses on a consumer good that contains plastic. Such verifiable passports are simplifying the sharing and retrieval of electronic information in a digitally supported circular economy. Examples for information in the product passport are the used plastic material, the recycling code, and the material's proof of origin.

What is special about the decentralised identifiers is that each market participant has its own trusted identity and contributes data to the final product passports in a self-determined manner. This means that the data is not provided by intermediaries, but that each participant is responsible for their own contributed data. All authorised market participants can e.g., see the data provided by the manufacturer or the manufacturer can see the data provided by a recycling company. The cryptographic signatures on the product passports allow all participants in a circular economy to determine who issued the product passport, if the product passport has been manipulated, and if the issuer was eligible to create the product passport.

One starting point for building trust in a circular economy is the creation of a decentral digital identity for all participants including waste management and recycling companies. This requires that all market participants along the plastic supply chain that want to contribute to a trusted product passport are equipped with a decentralised identity which is a DID that is connected to a private key and a corresponding DID Document that includes the public key (amongst other information).

With their private key, the market participants cryptographically sign the product information they provide, and that way create verifiable product passports stored in a material registry. Also, the product (or the product batch) receives a (passive) decentralised identity, so that it can be uniquely referred to and later lead the recycling enterprise to the material details. The use of identities per product batch mitigates the challenge of assigning unique identifiers for every single product although the product information stays the same.

Figure 3 shows how all market roles in the supply chain are equipped with decentralised, digital identifiers (managed by wallets) and how verifiable credentials, here in the form of a verifiable material and product passport, are created along the supply chain. All electronically signed passports are stored in decentralised databases, which we call the material/product (passport) registry. This registry is accessible to the authorised parties in the supply chain.

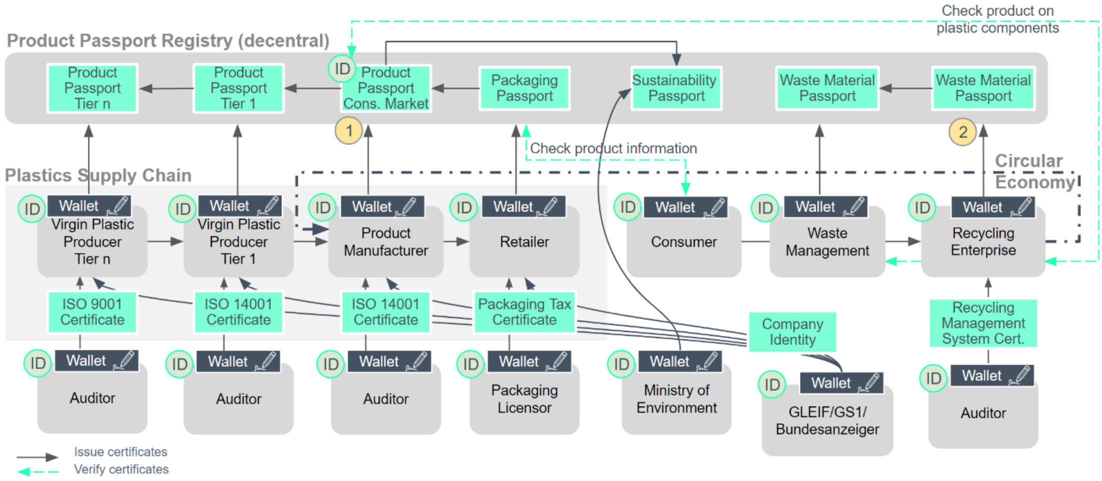

Figure 3: Functional Architecture: Physical Objects Flow and Data Flow with W3C Decentralised Identifiers and W3C Verifiable Credentials (digital Product Passport) for a Circular Plastics Economy. Own representation.

Other organisations can also add information to the registry by linking it directly to the manufacture DID or to the product DID. For example, a product sustainability certificate, like the German eco label “Blauer Engel” (sustainability passport), or a Product Ethics Passport, such as the “Fairtrade” certificate, can be registered for the manufactured product. Also, an auditor can add a proof-of-origin/quality certificate to the recycled material used in a circular economy-enabled product. This is again done, by issuing the respective information in form of a verifiable credential and adding it to the passport registry.

These audit documents create further trust into market participant and the information they provide. The product passport of the consumer product is linked to the product/material passports from the various material suppliers. Material information only exists one time; all verifiable credentials about one product together form the complete product passport. Verifiable credentials can be stored in different decentralised legers as well as classic central databases. Linking is possible due to cross-system capability of decentralised identifiers.

5.2 A typical information flow in the circular plastics economy

To establish a system of trust, first all involved companies need to create for themselves a W3C decentralised identifier with their wallet. Then they need to be equipped with a trustworthy decentralised identity, issued for example by a worldwide trusted institution such as a GLEIF (Global Legal Entity Identifier Foundation) issuer, the Bundesanzeiger Verlag or a GS1 accredited company. To increase the trust, companies can additionally request accreditation, for example an auditor certifies ISO 9001 or ISO 14001 compliance of a company. In our example the Virgin Plastic Producer of Tier 1 – n and the manufacturer have such certificates which they store in their wallet and which they can show to industry partners on request. Other possibilities to shape a decentralised identifier is to get credentials from the chambers of industry and commerce, banks or credit rating agencies, public authorities (trade office), e-procurement and supply chain business networks such as SAP Ariba, and product-related non-profit organisations like Fairtrade.

Now the digital product passport is produced: As a first step, as shown in Figure 3, the **virgin plastic producer** at tier n creates a digital product passport of its product and cryptographically signs it with its private key. An example for such a supplier in the plastic supply chain is the producer of plastic granules that delivers material to the tier 1 vendor. Then the **tier 1 virgin plastic producer** delivers the specific virgin plastics material to the manufacturer. An example is a classic vendor of packing material, such as the producer of plastic cups. This Virgin Plastic Producer issues a cryptographically signed product passport referring to the original tier n material, the transformation event and information about newly created tier 1 material e.g., the material identification code.

After the final production processes the **product manufacturer** issues a digital product passport for the consumer market including the final material identification code, and all other relevant information, e.g., information for the waste management and recycling company, and cryptographically signs it with its private key. At this point the decentralised identifier is printed on the product package in the form of a QR code or an alternative technology.

In the next step the **retailer** is responsible for the product packaging. To distribute the product the retailer needs a Packaging Tax Certificate which has to be issued by the **packaging licensor**. The distinct product, not the manufacturer, can receive a Product Sustainability Passport issued by the Ministry of Environment. All this information is linked to the product passport of the manufacturer, which remains the anchor for all information about the product and its suppliers. That means, the proposed concept allows transparency of the supply chain by linking all passports that are created during the value chain to one digital product passport.

The digital product passport for consumer products will be linked in practice to a product batch of a mass consumer product. Since the product passport focuses on the product batch and only on the raw materials used from a circular economy perspective, the digital product passport can remain the same until the materials change. A new product/material passport needs to be issued once the product “ingredients” change or if the product passport of one of the suppliers is changing. Such significant reduction of the number of digital product passports makes the proposed solution also suitable for **mass products.**

After the product has been distributed, used, and disposed by the **consumer**, it is disposed and collected by **waste management companies**. The waste management company reads the product identifier from the QR code on the product and uses it to retrieve the digital product passport. It can use the recycling information of the product passport of the original product and collect the material accordingly. It then issues a waste material product passport for a batch of collected material that includes all relevant information for the recycling enterprise.

The next and final step enables a trusted and verifiable circular plastics economy. The **recycling enterprise** checks the product passport of the waste material and creates a recyclate. The more information is available the more waste can be used for high quality mechanical recycling. We believe that through a better information flow along the supply chain, more material can be recycled, and new recycling methods can be developed. This can potentially lead to new recycling business opportunities and is subject to future work. For the recyclate the enterprise issues a recycling material product passport and signs it with its private key. This material can now be used by the manufacturer as a substitute for virgin plastic.

All information that has been issued as digital product passport or even as ISO 9001 certificate is verifiable. Every actor with a wallet and access to the respective VC can verify the information. That way, a consumer can check the product sustainability pass, the manufacturer can check the recycled material product passport or the ISO 9001 certificate of a virgin plastic manufacturer, and the waste management company can check the Proof of Origin of the virgin plastic product. This technology enables a full supply chain transparency and allows for a compliance check (e.g., to comply with the upcoming supply chain acts in Europe) within seconds.

The introduced technology allows on the one hand to close the information gaps between market participants without the need of a data intermediary and on the other hand to connect information from recycling industry with manufacturing information for a verifiable trustworthy circular economy.

5.3 Technical Examples of a Decentralized Product Passport for a Consumer Product

This subchapter contains code examples that are visualised as #1 and #2 in Figure 3. The following Figure 4 is the code example for the product passport published by the product manufacturer i.e., the number 1 in Figure 3.

```
{
    "@context": [
        "https://www.w3.org/2018/credentials/v1",
        "https://www.gs1.org/docs/gs1-smartsearch/gs1Voc_v1_3.jsonld"
        "https://www.example.com/circular_vocab"
    ],
    "type": [
        "VerifiableCredential"
    ],
    //this ID is the unique identifier of the product
    "id": "did:ethr:spherity:testnet:0x828efeeaab06dd9541992b791d78e5d96cd35323",
    //this is the DID of the manufacturer, please compare with the DID document below
    "issuer": "did:ethr:spherity:testnet:0xb80f2d123c799090a16cd6e28d401e28b41dc8fc",
    "issuanceDate": "2021-01-25T10:05:42.168Z",

    //use case specific i.e. Circular Economy specific properties
    "credentialSubject": {
        "astm": "D7611",
        "description": "Lorem ipsum dolor sit amet",
        "ewc": "150102",
        "gtin": "1234567",
        "hs": "1006.30",
        "identifier": "83627465",
        "materials": "R_1.1.6",
        "name": "ACME Joghurt",
        "producedSince": "2015-01-01",
        "recycledMaterialPass ":"did:ethr:spherity:test-
net:0x372b7201d9b8235d6943dfe574a6d243a6612c2f",
        "recyclingCode": "PP",
        "type": "Product",
        "id": "did:ethr:spherity:testnet:0x2b24bf07133bafb17d9521fbffb707ec06b6d34d"
    },

    //cryptographic proof of the values
    "proof": {
```

```
        "type": "EcdsaKoblitzSignature2016",
        "creator": "did:ethr:spherity:testnet:0xb80f2d123c799090a16cd6e28d401e28b41dc8fc",
        "created": "2021-01-25T10:05:42.168Z",
        "nonce": "131538ed-7040-49e6-85f4-f575b09a1b72",
        "domain": "https://spherity.io",
        "signatureValue": "gpO8DPntft-hz45PrJ_OOURKUuCjB10MfqYOR3q7LZ0C1E0watIn-
iaZSzbGY9B6APivzjc18QX_3uP7O6peHeQA"
    }
}
```


Figure 4: W3C Verifiable Credential for Digital Product Passport of a Consumer Product. Own representation.

The relevant data for the circular economy in the above code example is the material definitions (see element "credentialSubject"). Fundamentally new in this scientific work is the representation of the digital product passport in the format of a W3C verifiable credential and circular economy specific embedded data schemes as extensions. Since the data scheme for the use case and the properties desired by the market have not yet been standardised, we use the following example data:

- product name and product description.
- European Waste Catalogue (EWC) code for the classification in the waste collecting processes.
- Recycling Code a.k.a. ASTM International Resin Identification Coding (RIC) System
- American Society for Testing and Materials (ASTM) code.
- Global Trade Item Number (GTIN) code example of the GS1 system - colloquially also called product barcode.
- Harmonized (Commodity Description and Coding) System (HS) example.
- an example for a Recycled Material Standard (RMS) Framework inside the material property

The values are exemplary and only for visualisation purposes of the capabilities of this technology. Waste specific properties in the Verifiable Credential are the benefit of this proposal; multiple data scheme standards and multiple perspectives of the supply chain can be used in single product passports that all authorised market participants can access. Special properties such as color, plasticisers and additives could also be added here if that is requested by the recycling companies. The schema, further internationalisation and globalisation, and more specifics in the value are topics for further research. In principle, however, international material standards need to standardise this data vocabulary so that all players in the market (manufacturers, waste, and recycling companies) have a common understanding of the data and its semantics. The paper industry has thus already developed an international standard with EN 643 for wastepaper qualities including grade-specific limits for unwanted materials. This standard could also be used to describe the recycling material quality.

As already described above, digital product passports for mass products do not vary in the individual products. Therefore, it makes sense to create a passport (and a product DID) per **product batch.** The product passport changes once a different material is used in production. Technically, this can be implemented by issuing a digital product passport that is valid for all products between the time stamp of the first production (`producedSince`) and a subsequent digital product passport (see example in Figure 4).

Material recycling for packaging materials is a mass production process. Links between recycling material and collected products would be possible in theory but the required data volume and data confidentiality might prevent it. Therefore, a more practical option would be for recycling companies to issue new product passports and establish trust by linking it to the product passport of the waste collection companies. Waste collection companies are already required to share their collection **quantities** and prepare **waste balances** today, so that when full coverage is achieved, the quantities of certified recycled material can then be plausibilised with the quantities of waste collected. Both approaches are conceivable for the certification of the origin of recycling materials. A recommendation should be determined from further research.

Furthermore, the element `recycledMaterialPass` contains a DID that references to the recycling material product passport shown in Figure 6. Multiple references will be needed in practice. The recycling material product passport is cryptographically signed and can therefore be verified by anyone. Further research is needed to analyse the required data of a product passport, which will then lead to new use cases, e.g., an increased usage and consumption of recycling materials or new recycling methods.

```
{

  "@context": [
    https://w3id.org/did/v1 ],

  //this is the DID of the manufacturer  "id":
"did:ethr:spherity:testnet:0xb80f2d123c799090a16cd6e28d401e28b41dc8fc",
  "service": [ {
      "type": "agent",
      "serviceEndpoint": "https://spherity.api.wallet.eu.spherity.io/api/v1/inbox"
    }],
  "authentication": [ {
      "type": "Secp256k1SignatureAuthentication2018",
      "publicKey": [
      "did:ethr:spherity:testnet:0xb80f2d123c799090a16cd6e28d401e28b41dc8fc#owner"]   }],
  "publicKey": [ {
      "id": "did:ethr:spherity:testnet:0xb80f2d123c799090a16cd6e28d401e28b41dc8fc#owner",
      "type": "Secp256k1VerificationKey2018",
      "ethereumAddress": "0xb80f2d123c799090a16cd6e28d401e28b41dc8fc",
      "owner": "did:ethr:spherity:testnet:0xb80f2d123c799090a16cd6e28d401e28b41dc8fc"
    }
}
```

Figure 5: Product manufacturer DID Document. Own representation.

The example in Figure 5 does not include further company details but the W3C DID standard also allows to include legal company name and common, externally defined identifiers such as the sales tax numbers, Data Universal Numbering System (DUNS) and other legal identifiers.

Figure 6 shows a simple code example of a W3C VC-based recycled material product passport that was filled and cryptographically signed by the recycling company.

```
{
    "@context": [
        "https://www.w3.org/2018/credentials/v1",
        "https://www.gs1.org/docs/gs1-smartsearch/gs1Voc_v1_3.jsonld"
          "https://www.example.com/circular_vocab"
    ],
    "type": [
        "VerifiableCredential"
    ],
    //this ID is the unique identifier of the recycled material    "id":
"did:ethr:spherity:testnet:0x372b7201d9b8235d6943dfe574a6d243a6612c2f",
    //this isser-ID is the unique identifier of the recycling enterprise
    "issuer": "did:ethr:spherity:testnet:0x477f65f366e34afadc1ef79d293b875a8812778a",
    "issuanceDate": "2021-01-25T10:00:07.230Z",

    // use case specific i.e. Circular Economy specific values
    // Recycled Material Standard (RMS) Framework is used as in example
    "credentialSubject": {
        "materialGroup": "plastic",
        "materialIDCode": "R_P1.1.6",
        "materialType": "recovered PET",
        "recyledStatus": "recycled",
        "id": "did:ethr:spherity:testnet:0x5e6323230f4e144f967dc953be8aced1d936e3cf"
    },
    "proof": {
        "type": "EcdsaKoblitzSignature2016",
        "creator": "did:ethr:spherity:testnet:0x477f65f366e34afadc1ef79d293b875a8812778a",
        "created": "2021-01-25T10:00:07.230Z",
        "nonce": "46b2eb9c-3f3a-4d29-ada0-a3ce064bdb14",
        "domain": "https://spherity.io",
        "signatureValue":
"uAnNESoIc6EyQEiO_oxvSpAkAcLb04ceAJPWiukCym12rX1sTMOgaK15qriNFDG3Bzhmy1ZL07VBpCvzI6WE8gE"
    }
}
```


Figure 6: W3C Verifiable Credential for Recycled Material Passport. Own representation.

The section `credentialSubject` is domain specific in this W3C Verifiable Credential for recyclate materials. In this paper we are using the Recycled Material Standard (RMS) Framework to describe the recyclate[19]. In a further step, additional properties could be added also for 3rd party certifications such as the standardisations from ISO/TC 323 Circular Economy[20]. The right data scheme and its domain specific properties for an ideal Circular Economy is not focus of this paper and requires further research and standardisations. The document itself has a cryptographic signature (see element "`proof`") that ensures the immutability and therefore the trust in the information.

[19] To prevent fraud, we are proposing to add some further data for plausibility checks such as the waste collection area (zip code or geo location). Such example properties are not included in this code example and should be analyzed in further research

[20] See https://www.iso.org/committee/7203984.html and the ISO/AWI 59040 Circular Economy — Product Circularity Data Sheet https://www.iso.org/standard/82339.html

```
{
  "@context": [
    "https://w3id.org/did/v1"
  ],
    //this ID is the unique identifier of the recycling enterprise  "id":
"did:ethr:spherity:testnet:0x477f65f366e34afadc1ef79d293b875a8812778a",
  "service": [
    {
      "type": "agent",
      "serviceEndpoint": "https://spherity.api.wallet.eu.spherity.io/api/v1/inbox"
    }
  ],
  "authentication": [
    {
      "type": "Secp256k1SignatureAuthentication2018",
      "publicKey": [
        "did:ethr:spherity:testnet:0x477f65f366e34afadc1ef79d293b875a8812778a#owner"
      ]
    }
  ],
  "publicKey": [
    {
      "id": "did:ethr:spherity:testnet:0x477f65f366e34afadc1ef79d293b875a8812778a#owner",
      "type": "Secp256k1VerificationKey2018",
      "ethereumAddress": "0x477f65f366e34afadc1ef79d293b875a8812778a",
      "owner": "did:ethr:spherity:testnet:0x477f65f366e34afadc1ef79d293b875a8812778a"
    }
  ]
}
```


Figure 7: DID Document of the recycling enterprise. Own representation.

The definition of required properties for a recycling company requires further research, however this identifier is used in the product passport for the recycling material in Figure 6.

5.4 Trust and Authenticity

The W3C verifiable credential standard includes state of the art cryptography to build trust into the issued credential. The `proof` section contains the signature, which proofs not only that the credential was not changed but also who issues and signed it. The trust in the digital identities and signatures of the market participants (Figure 5 and Figure 7) is an important topic to address, when using the introduced decentralised technology.

One variant to provide trust is to use the already established web domain's reputation. W3C's recent draft for a did:web Method Specification[21] uses the established trust of market participant's websites. In this method, the X.509 certificate of a trusted domain, such as sap.com, secured by a central public key infrastructure (PKI) is leveraged to securely manage the DID document. In this method the DID document containing the public key is stored at the well-known location of the domain (for instance the example URL according to did:web https://www.sap.com/.well-known/did.json). When a signature in the proof section of a credential is verifiable

[21] See did:web Method Specification - Draft Community Group Report 20 December 2021 https://w3c-ccg.github.io/did-method-web/ , the previously discussed X.509 DID method https://github.com/WebOfTrustInfo/rwot9-prague/blob/master/topics-and-advance-readings/X.509-DID-Method.md and other currently discussed authentication concepts (see https://www.researchgate.net/publication/342027346_Distributed-Ledger-based_Authentication_with_Decentralized_Identifiers_and_Verifiable_Credentials)

with the public key of that DID document, the verifier has a cryptographic proof that the credential has been issued by the controller of the domain (here sap.com). Now the verifier can trust the market participant's decentralised entity and the verifiable credentials s/he issued and therefore trust the digital product passports. The `did:web` method can be used instead of the `did:ethr` method we described in Section 3 to anchor a DID.

6 Summary and Discussion

This paper has investigated the potential of novel digital instruments to alleviate current market failure in the circular economy market for plastics induced by information deficit and its consequences. These instruments can be used to lower or eliminate the informational barriers and the lack of trust inherent to the market for secondary plastic materials that at present hinder the emergence of a fully functional circular plastics industry.

We analysed the technical approach using decentralised identifiers and verifiable credentials as means to provide a consistent and uninterrupted chain of documentation. Through such an uninterrupted chain for a given product or batch it can be traced and tracked validly and reliably. The product can take alongside the information required to enable the reapplication of recycled plastics material which depends on the qualities and capabilities of the material and the treatment it experienced in its production and consecutive use. Decentralised identifiers and verifiable credentials can therefore be seen as an enabling step towards digital product passports as envisioned by current circular economy-related research and political strategies.

We validated W3C standard-based decentralised product passports with this research paper on an experimental level. This technology currently exists on readiness level (TRL) 5 and is thus in an advanced stage for productive adoption. To apply the technology in the circular plastics economy, the industry has to agree on a few basics:

- A common vocabulary needs to be developed by the market actors that fulfill the circular plastics economy use case. Also, the semantics of the vocabulary must be clearly defined for each attribute in a verifiable credential/product passport.
- It needs to be defined what actors may access which information of the product passport registry; what information should be public or private. According access control mechanisms need to be configured to protect e.g., trade secrets.
- It has to be decided what DID-methods to use for which market participants, e.g., did: web for large well-known companies in combination with did:ethr for smaller players.
- For each product, there needs to be a discussion of how large the batch size should be that is referred to in the product passport.

For the management of the circular plastics supply chain, the technology shown can provide a vessel for suppliers and manufacturers to not only signal but also demonstrate the value of a given type of plastics. Information stored in a product passport accompanied by a clear and incorruptible identity can create the **market transparency** that is currently lacking not only in the circular plastics economy, but also in many other fields. In effect, these technologies enable an automatised monitoring of the product use and markets.

Consequently, **transaction and search costs** should decrease leading to more attractive markets through cheaper and safer use of plastic recyclates. Furthermore, the information gained can inform the plastics producers and manufacturers more deeply on the use and application of plastics in their respective markets. **New**

recycling streams can be built on more and trustworthy information. **Better-informed decisions** on product and process design could be made leading to further improvements in resource and energy efficiency.

However, some questions remain. E.g., it needs to be decided who will manage, control and cover the introduction and management of such a system. Moreover, the related costs need to be distributed and as of now need to be fully calculated. But, since the introduction of the identifiers and the subsequent passport should start at the virgin material level, they will not be attributed to secondary material alone. Ideally, the costs should be covered with the purchase of primary material to reduce its price advantage.

Political decision makers on several levels have postulated the necessity of introducing **product information systems** such as passports to boost the chances of circular economy markets and business models. The European Commission has even announced the introduction of a battery passport by 2026 which can be designed and implemented in the same way as shown in (Guth-Orlowski,21). Given the current state of the economy and functioning of markets, it will be indeed a **governmental task** to commission the creation and basic operations of such systems to secure functionality, compliance with ecological requirements and access to the system for all companies and participants, especially SME's. We suggest that the establishment of such systems should best be made on an international level, e.g., at least EU-wide. Different systems and standards dispersed over different nations will only create new market dysfunctionalities. Hence, **interoperability** and data integration should be guaranteed at the highest geographical level possible. A further desideratum may be the inclusion of additional information required by the **supply chain act** (German: Lieferkettensorgfaltspflichtengesetz (LkSG)). This would make the digital product passport a single point of information for a given product or material.

Identities and passports may also provide governments with much better chances to **monitor compliance** themselves and to improve their understanding of circular markets. We hence suggest a dynamic system able to be adapted based on these findings or other new requirements.

Many analyses and assessments have pointed out the **ecological potential of a circular economy** per se. Plastics recycling itself has the potential to considerably cut GHG-emissions, varying with the specific type of plastics. We hence see a huge advantage in digitally improving and even enabling plastics recyclate markets. However, with the introduction of and consecutive use of digital technologies, the danger of rebound effects emerges. The measures taken may create more environmental harm than they reduce. Hence, digital systems to support a resource and energy efficient circular economy need to be monitored for their energy and resource requirements.

7 Literature

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