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A Digital Product Passport for Critical Raw Materials Reuse and Recycling

Rembrandt H. E. M. Koppelaar [1], Sreenivaasa Pamidi [1], Enikő Hajósi [1], Lucia Herreras [2], Pascal Leroy [2], Ha-Young Jung [1], Amba Concheso [3], Radha Daniel [3], Fernando B. Francisco [4], Cristina Parrado [4], Siro Dell'Ambrogio [5], Fabiana Guggiari [5], Deborah Leone [5] and Alessandro Fontana [5,*]

[1] EcoWise Ekodenge Ltd., 8 Kean Street, London WC2B 4AS, UK
[2] WEEE Forum a.i.s.b.l., Boulevard Auguste Reyerslaan 80, B-1030 Brussels, Belgium
[3] DSS+, 70 Gracechurch Street, London EC3V 0XL, UK
[4] CARTIF Technology Centre, Parque Tecnológico de Boecillo, 205 Boecillo, 47151 Valladolid, Spain
[5] SUPSI DTI, La Santa 1 Street, 6962 Viganello, Switzerland
* Correspondence: alessandro.fontana@supsi.ch

Abstract: The reuse and recycling of critical raw materials is limited, as waste electrical and electronic recycling focuses on base and precious metals, and device component reuse is in its infancy. To help to address this issue this paper provides the conceptual design of a Digital Product Passport based circular supply management system. To enable the recovery of critical raw materials at component and material levels for reuse and recycling. The works include an assessment of existing critical raw materials information management and an information needs identification survey, with 10 manufacturers, producer responsibility organisations, collectors and recyclers. The needs were used to generate 14 key product information management processes and exchanges that when implemented form a Digital Product Passport based circular supply management system. Information managed via a physical-digital linkage through individual product tags includes product registrations, materials declarations, life cycle status updates, the sorting of products at collection points based on critical raw material contents, and flagging of products for critical raw materials component extraction. A dataspace-based IT systems architecture is proposed for the implementation of the supply management system taking into account global and European information standards. Finally, key challenges to implement such an IT architecture are discussed.

Keywords: circular economy; digital product passport; recycling; reuse; critical raw materials; waste electrical and electronic equipment; dataspaces

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1. Introduction

The growing supply requirement of several material resources needed for industrial society and the low carbon transition are a growing concern. The current issue is mainly the risk of cost pressures within supply chains, as experienced in recent years, primarily due to the geographic mining and manufacturing concentrations making supply chains vulnerable to shocks caused by different supply side restrictions [1]. In an annual McKinsey survey, 83% of 113 firms with large supply chains stated they experienced shortages in the year 2021–2022, either at material or at component levels, partially caused by the COVID-19 pandemic [2]. Shortages, which in this context are of a temporary nature, result in production delays due to a lack of materials availability and cost pressure from price fluctuations [3,4]. The experienced shocks in supply chains warrant greater concern of the possibility of export quotas or embargo's imposed by one or a few countries that produce the majority of a material which can cause shortages with longer lasting significant economic impacts [5]. Supply side shortages can also be caused by a lack of newly developed brownfield mine-sites to increase production and replace depleted mines in the face of swiftly growing demand. Shortages of materials such as Cobalt, Indium, Lithium and

Neodymium can severely hamper the speed of the zero-carbon energy transition as these are necessary for expansion of batteries and renewable energy technologies [6]. In the latest 2021 assessment of material needs for the energy transition the International Energy Agency concludes that: ''looking further ahead in a scenario consistent with climate goals, expected supply from existing mines and projects under construction is estimated to meet only half of projected lithium and cobalt requirements and 80% of copper needs by 2030." [7].

The issue of materials shortages in the European Union (EU) at a political level was brought into focus since 2011 by issuing a declaration of Critical Raw Materials (CRMs), a list now containing 30 CRMs. The European Commission through the EU Joint Research Centre updates this list every three years based on two parameters with thresholds to define a CRM, their economic importance and supply risk [8]. For example, the EU imports 93% of its magnesium from China and as a result of this dependency and its economic importance, magnesium is included in the list of CRMs [5]. The CRM list provides a narrower set of materials to focus EU economies in their efforts towards abatement and mitigation of supply chain risks.

A key mitigation solution, which forms the rationale for this study, is the boosting of CRMs recycling and reuse of CRM containing components from products including Waste Electrical and Electronic Equipment (WEEE). At present few CRMs are recycled at a substantive scale. Out of 30 CRM's there are 14 with a very low global end of life recycling rate of 0% to 5%, such as Bismuth, Indium, and Gallium, and another 6 with a low global end of life recycling rate of 6% to 30%, such as Tantalum, Tungsten and Germanium [9]. To boost CRMs recycling and component reuse, improved supply management systems, practices and technologies are needed, that serve to keep products and materials in the reuse and recycling loop as long as possible [10]. In this context, supply management systems need to achieve two recovery goals:

- To extract components containing CRMs from used devices in the treatment and recycling process so as to enable direct re-use or after repair, and enhance recyclability of CRMs. The effort enhances component supply and reduces the need for virgin component manufacturing;
- To enable separation and recycling of CRMs to produce secondary raw materials, both in high quantities and at purity levels fit for inputs into manufacturing supply chains, to reduce the need for virgin materials mining.

Both goals are related as extraction of components is often a necessary step prior to recycling, as otherwise the CRM or CRMs will be mixed with other materials in the treatment process where products or part of products are shredded for sorting, making it much more difficult to extract and recycle the materials. The separate extraction and processing of CRM components enhances the technical and economic feasibility of tailored CRM recycling facilities [11].

The key objective in this paper to address the issue of materials shortages, and in particular CRM shortages, is to provide for a conceptual design of a supply management system that enables the recovery of CRM at component and material levels using CRM information exchanged through Digital Product Passports. A Digital Product Passport makes a product universally identifiable and its information accessible both offline and online through a web-portal on the internet. The works carried out described in this paper are part of the EU funded four-year CircThread project, which together with 31 organisations is piloting a wide range of information management and exchange approaches to boost the circular economy of Electrical and Electronic Equipment (EEE) using Digital Product Passports. CircThread which stands for Circular digital Thread seeks to provide for a dynamic updating of information across a products life-cycle forming a Digital Thread building upon its definition.

The works are described in the paper following the traditional: a brief literature overview of Digital Product Passports (Section 2), the methodology (Section 3), results (Section 4) and conclusions (Section 5).

2. An Overview of Digital Product Passports

The concept of a Digital Product Passport has been identified as a container that integrates various datasets about a product from all its life cycle phases [12]). It forms a new digital format to digitise and modernise product data to support industry transformation towards circularity and carbon neutrality [13], including legal and/or voluntary data [14]. Features of a Digital Product Passport can include the ability to trace a products life-cycle history, as well as to track it as it is moving from location to location [13]. The information in the Digital Product Passport can be made accessible online through the internet and offline via physical product tags such as QR codes [15]. Different variants can exist in terms of static or dynamic Digital Product Passports, where a static passport can only be read by actors across the product life cycle, whilst in dynamic ones stakeholders along the lifecycle can read and write content into the passport [16]. The EU Ecodesign for Sustainable Products Regulation legislation proposed by the European Commission in March 2022 is the first legislation that will institute the European framework for Digital Product Passports [17]. The legislation will likely come into force in 2024 after the trilateral process between the European Commission, European Parliament and European Council is concluded. Subsequently, in specific further legislation the Digital Product Passports requirements will be defined for specific product groups as part of the EU sustainable products initiative.

The definition we adopt here of a Digital Product Passport is that of a container for datasets that is accessible through the internet via online and offline access points. The basis of a digital product passport is a universal product identifier connected to unique internet identification. Several product identification systems are already common, such as legally required product serial numbers and Global Trade Identifier Numbers (GTINs) [18]. To make Digital Product Passports work these will need to be enhanced to make products uniquely identifiable on the internet, such as via a weblink or web address, based on a Uniform Resource Identifier (URI) that forms the basis of a Universal Resource Location (URL). Once the product has a home on the internet, information about the product can be listed and made accessible in a Digital Product Passport format. This opens up opportunities to provide technical, environmental and circularity product information in one central location on the internet. The final aspect is to physically tag the product with the linked product identifier codes and URIs using a QR code, or a similar physical data tag containing readable information accessible to a user such as a collector or recycler via a mobile device.

The introduction of Digital Product Passports can provide for a digital vehicle to make accessible in a central location on the internet product life cycle data. A key benefit that this provides is to end the isolation of data pools and information sets within specific organizations, so as to improve the circular economy and sustainability of products. Both in terms of connecting specific actors across a product's life cycle and by making information generally available, depending on the public or private nature of the information that is exchanged. A second benefit is that information can be more easily retrieved, requested, or provided and shared by any actor across the product life cycle. And a third benefit is that the information can be provided in a flexible manner at product model, batch, or even at individual product level.

A large number of use cases can be envisioned and many have yet to be explored in this new digital innovation. The most advanced is the vehicle and industrial battery passport, which is to be mandated under the EU batteries regulation from January 2026 in the European Union. The passport mandated contents are still to be specified in an EU delegated act by December 2024 [19]. The first state of the art exploration of use cases for the Digital battery passport was published in June 2022 [20]. A few more general use case examples include: a standardised repair log such that repair organisations and manufacturers can retrieve individual device repair histories or across a product model from repair technicians outside of their own repair services; material declarations from manufacturers that enable recyclers to improve their sorting and recycling processes; a product purchasing comparison scorecard for consumers based on sustainability and social indicators such as Product Environmental Footprint (PEF) and social hotspot analysis; marketing information provisioning by retailers to consumers when they register a product breakdown in the digital product passport of their product; and a standardised disassembly effort log such that pre-treatment, refurbishment and remanufacturing operators can identify the pain-points and time consumption in disassembly for manufacturer product design improvement feedback.

One of the first overviews about current initiatives to develop the concept and implement Digital Product Passports can be found in a recent Wuppertal Institute working paper [21]. Future overviews will be established in the Digital Product Passport initiatives review from the EU funded CIRPASS project, www.cirpass.eu that lasts from 2022 to 2024 [22].

3. Methodology

The development of the Circular CRM supply management system concept was carried out through four development stages (Figure 1) to provide for a comprehensive design: goals definition; information collection and needs surveys with organisations involved in the product life cycle; Circular CRM supply management information workflow assessment; expert-based Circular CRM supply management IT system design.

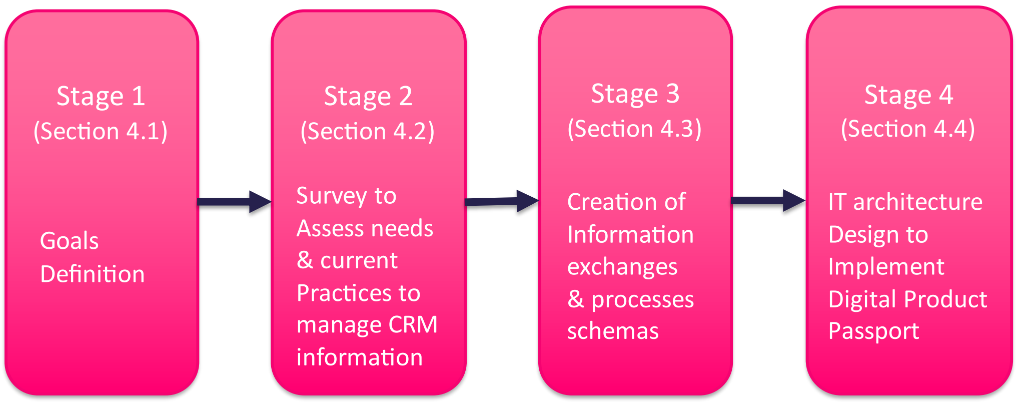


Figure 1. Overview of the development stages carried out to design the circular CRM supply management system.

The first stage was to define the high-level goals, which was carried out in September 2020 as part of the CircThread project grant proposal delivery, in response to the requirements set by the EU commission for the H2020 research funding call SC5-31 'Develop, Implement and Assess a Circular Economy Oriented Product Information Management System for Complex Products from Cradle to Cradle' [23]. The defined objectives of the EU call included: 'achieving the targets of the IP on Raw Materials particular in terms of feeding secondary raw materials knowledge into the EC Raw Materials Information System (RMIS)' and a selection of products that are 'linked for both ends of the lifecycle to critical resource issues . . . with products that may contain critical raw materials'.

Second, during the project from October 2021 to April 2022, the needs and current practices to manage the information about materials and CRMs were evaluated with the relevant CircThread project partners. This includes five manufacturing organisations covering home appliances, solar glass, battery systems and home heating devices manufacturing, as well as one collection company, two producer responsibility organisations, and two recyclers. This was done via two standardised surveys sent to these partners. The purpose of the first survey was to elaborate on product life cycle stakeholder needs for circular economy information, including the needs to enhance component recovery and recycling of CRMs. Specifically, the survey was designed to collect information about: the life cycle actor; the role of this actor; the challenges in relation to the management of CRM's; and the goals to be achieved with a Circular CRM supply management system. The purpose of the second survey was to identify currently available information about the products that are manufactured or handled, including the information for declaring and/or tracing materials in general, and CRMs in particular. Both surveys were evaluated in post-survey collaboration meetings with each individual partner to add further details and explanations within the Research & Innovation project context. The results displayed in this study have been generalised so as to not allow for identification of particular information to an individual organisation.

Third, the information exchanges and information processing required to fulfil the needs for Circular CRM supply management using Digital Product Passports was elaborated. To this end, an examination of the required product life cycle actors that can provide and use the information was made. This included: what information would need to be exchanged between them; how this information could be exchanged from a software perspective; and what interactions are needed between organisations and their employees identified by job roles and different software systems. The approach was carried out using Business Process Modelling Notation (BPMN) and expert reasoning to create an overview of the required information exchanges across the product life cycle for Circular CRM supply management. Workshops were organised with the product life cycle partners to verify the proposed information flows. The final resulting process workflow diagrams show the information flow and actions that need to be undertaken for involved organisations across the product life cycle.

Finally, based on the earlier stages a synthesis was made presented in this paper to conceptualise the architecture of a Circular CRM supply management system for components and materials across the life cycle of products. The methodology here uses expert knowledge to integrate the information process flows with an IT architecture design and existing information management systems and standards. To this end, international and European standards were screened to assess those relevant for structuring information exchanges.

In all stages relevant industry, legal and academic literature have been consulted to deepen understanding. The approach here was not to create an exhaustive evaluation as standard in literature reviews or meta-studies. Instead, the design of the Circular CRM supply management system was grounded in some of the most relevant available works. These were identified based on either the number of citations, a selection of standards from a review of available industry standards, and an evaluation of directly applicable EU legislation. This process was guided by involvement of expert CircThread project partners to guide respective bodies of work, including a national standardisation body, an environmental NGO with legislative experts, a Producer Responsibility Member Organisation, and three universities.

4. Results

4.1. High Level Goals

Background research was carried out during the project grant proposal, now grant agreement, to define the goals for which the CRM supply chain management should be defined. The resulting strategic goals in the grant agreement based on the proposal submitted in September 2020 include the following: "CircThread will improve tracing of both non-critical and the updated 2020 list of 30 Critical Raw Materials (CRM) … CircThread will do this first by linkage of product raw materials and secondary raw materials information at different life cycle stages to its digital product log and tracing." [24]. "Second by providing sampling data to update the current Raw Materials System Analyses (RMSA) in the EU Raw Material Information System … to this end a service mechanism for transmission of collected and recycled product materials data will be delivered to external information providers." [24]. The proposal also stated that "CircThread will support enabling the monitoring across the life cycle chain by establishing % visibility of product composition and % traceability across the extended life cycle indicators." [24].

4.2. Needs and Current Practice for Materials Information Management

The needs were assessed with CircThread partners in a survey based on an information template as described in Section 2. The results shown in Table 1 below cover the needs of Original Equipment Manufacturers (OEMs), Producer Responsibility Organisations (PROs), collection companies and recyclers. A PRO is an organisation that is authorised and financed by manufacturers to operate and manage schemes for the collection and reverse logistics of waste, in this context Waste Electrical and Electronic Equipment (WEEE), at their end-of-use to ensure their sound environmental management including recycling processes. In the EU PRO's for WEEE have been in operation since 2003 when the EU commission's WEEE Directive came into force.

Table 1. Needs for a Circular CRM supply management system from OEMs, collection companies and recyclers.

Life Cycle Actor	Persona	Role	Pain Points in CRM Context	Needs
OEM	Production Manager	The production manager has to know the availability of raw materials needed to organise the production line.	Some raw materials, including critical raw materials, have a high-supply risk due to the very-high import dependence.	To avoid supply risks and organise the production in the best way possible. To improve knowledge about the critical raw materials market.
OEM	Sustainability staff/manager	This staff is dedicated to ensure the products sustainability and uses information to evaluate the product and the company.	To comply with sustainability legislation, it is necessary to know the critical raw materials legislation that will be established by the European Commission.	Having a complete knowledge of the evolution of critical raw material. Keep up to date with the legislation about CRMs.
OEM	Quality manager	The quality manager defines the standards for the product and components. Normally, the standards are set based on technical requirements.	It is not possible to obtain the right information on the final phase of pre-treatment and recycling of the product.	To increase the knowledge about what happens with our products during the pre-treatment and recycling phase.
Municipal collection company	Collection centre operator	Supervision and management of the activity of waste disposal performed by the citizens.	Handling products without knowing accurately their composition. Not knowing if in the products there are CRM.	Create a separate collection cluster for products containing a high amount of CRM, to increase the recycling of CRM.
Municipal collection company	Collection Administrator	In charge of decisions regarding the processes to be implemented and to manage the company cashflows.	It is extremely difficult to understand in advance the economic benefit of certain operations including the removal of components to recover CRM.	Develop treatment activities dedicated to products containing a high amount of CRM. Improve the decision-making process in terms of incoming/outgoing material flows, to better assess economic offers and develop ad hoc operating procedures to manage products flows.

Table 1. *Cont.*

Life Cycle Actor	Persona	Role	Pain Points in CRM Context	Needs
Recycling facility	Recycling facility manager	The recycling facility manager deals with electric and electronic waste from different sources and is an expert in the recovery of ferrous and non-ferrous metals, having experience in material handling and recovery.	It is not possible to get the right information for some of the components/materials arriving to the plant, such as the composition, how they were used, and disassembly routes. This information would optimize the recovery and enable the implementation of the circular economy principles.	Increase the knowledge about incoming materials and components. Provide the manufacturers with valuable information. Automate the decision-making process for site management. Increase revenue from selling recovered products and spare parts. Implementation of new collaborative business models resulting in economic advantages.

Based on the survey with organisations a Circular CRM supply management system should cover the following eight needs:

1. To reduce the risks associated with the lack of CRMs' availability as inputs in manufacturing systems (OEMs);
2. To ensure compliance with legislation for CRM management (OEMs);
3. To enable separation of products with high CRM content during collection at end-of-use (collection companies);
4. To enable calculation of CRM material in/outflows at collection points for reverse logistics (collection companies; PROs);
5. To enable identification of product components with high CRM content for extraction/disassembly (collection companies; recyclers);
6. To make visible what happens to CRMs in products during pre-treatment and recycling (OEMs);
7. To enable economic calculations about the value of CRMs from component recovery and recycling so as to unlock investments in new operations and processes (collection companies; recyclers);
8. To make it possible to create collaborative business models between OEMs, PRO's, collection companies and recyclers for CRM management.

The current practices for materials information management in a broader sense were assessed in a separate survey with 10 organisations using a different information template, as also described in Section 4. The results are shown in Table 2 below. The survey shows that at present there is no CRM specific product/materials information management in place.

Table 2. Overview of available materials information at OEMs, collection companies, PROs and recyclers. The number of organisations that currently have the information available is shown.

Information Item	Number of Organisations with Available Information Items			
	OEMs (5)	**Collection Company (1)**	**PROs (2)**	**Pre-Treatment and Recycler (2)**
Availability of product/materials information				
Supplier bill of materials	2/5			
Supplier component information sheet	1/5			
Product bill of materials *	5/5	0/1	0/2	0/2

Table 2. *Cont.*

Information Item	Number of Organisations with Available Information Items			
	OEMs (5)	Collection Company (1)	PROs (2)	Pre-Treatment and Recycler (2)
Product information sheet as manufactured	5/5	0/1	0/2	0/2
Product material composition information	2/5	0/1	0/2	0/2
Information sheets for disassembly of the product **	0/5	0/1	0/2	0/2
Product component recycling performance information sheet	0/5	0/1	0/2	0/2
Secondary raw materials cost/price data	2/5	0/1	1/2	2/2
Periodic report on products processed per month		0/1	2/2	2/2
Quantity of material provided in the recycled material streams		0/1	2/2	2/2
Pre-treatment process options information		0/1	2/2	1/2
Availability of CRM specific product/materials information				
Product CRM material information sheet	1/5	0/1	0/2	0/2
Product component CRM information	1/5	0/1	0/2	0/2
CRM information log for product/waste sent to pre-treatment facility or disposal facility		0/1	0/2	0/2
CRM treatment options evaluation to provide required quality standard information	0/5	0/1	0/2	0/2
Technical requirement for quality of CRM materials recovered for secondary raw material use	0/5	0/1	0/2	0/2
Estimated recovery potential of CRM materials in product	0/5	0/1	0/2	0/2
Estimated recovery potential of CRM contained in components	0/5	0/1	0/2	0/2
Future recycling trends for CRMs	0/5	0/1	0/2	0/2

* The Bill of Materials in 2/5 does not contain materials information in the listing of all parts/components; ** Only available for particular products when required according to regulations such as for displays (EU WEEE Directive Annex VII). At the point of disassembly processes are normally carried out based on expert and tacit knowledge, and are not captured in an information sheet.

The current information management practice is as follows among this organisation cohort:

9. OEMs manage product information through a product Bill of Materials (BOM) which provides a structured listing of the components in a product, but it does not necessarily contain materials data per component. Only OEMs with less complex products in terms of number of components have a list available of overall material composition information in % contained in the product, such as captured in Material Safety Data Sheet (MSDS). Four out of five OEMs do not collect or manage any CRM specific information. Disassembly information is not generated to extract specific components to assist pre-treatment operators.
10. Collection companies do not manage or collect any product/materials flow or quantities information broadly or for CRMs.
11. Producer Responsibility Organisations manage periodic reports on products processed per month per WEEE (Waste of Electric and Electronic Equipment) category and have

an overview of pre-treatment process options for reverse logistics management. They also receive from recyclers annual reports on the quantity of materials provided in recycled material streams, but this is not product specific. The PROs do not manage any CRM specific information.

12. The pre-treatment operators and recyclers process information on the products quantities processed per month per WEEE category. They also evaluate the quantity of materials by material type in recycled materials streams, but this is not product specific. They do not manage any CRM specific information. Disassembly information is not generated and captured at a product specific or product category level but based on expert and tacit knowledge of processes.

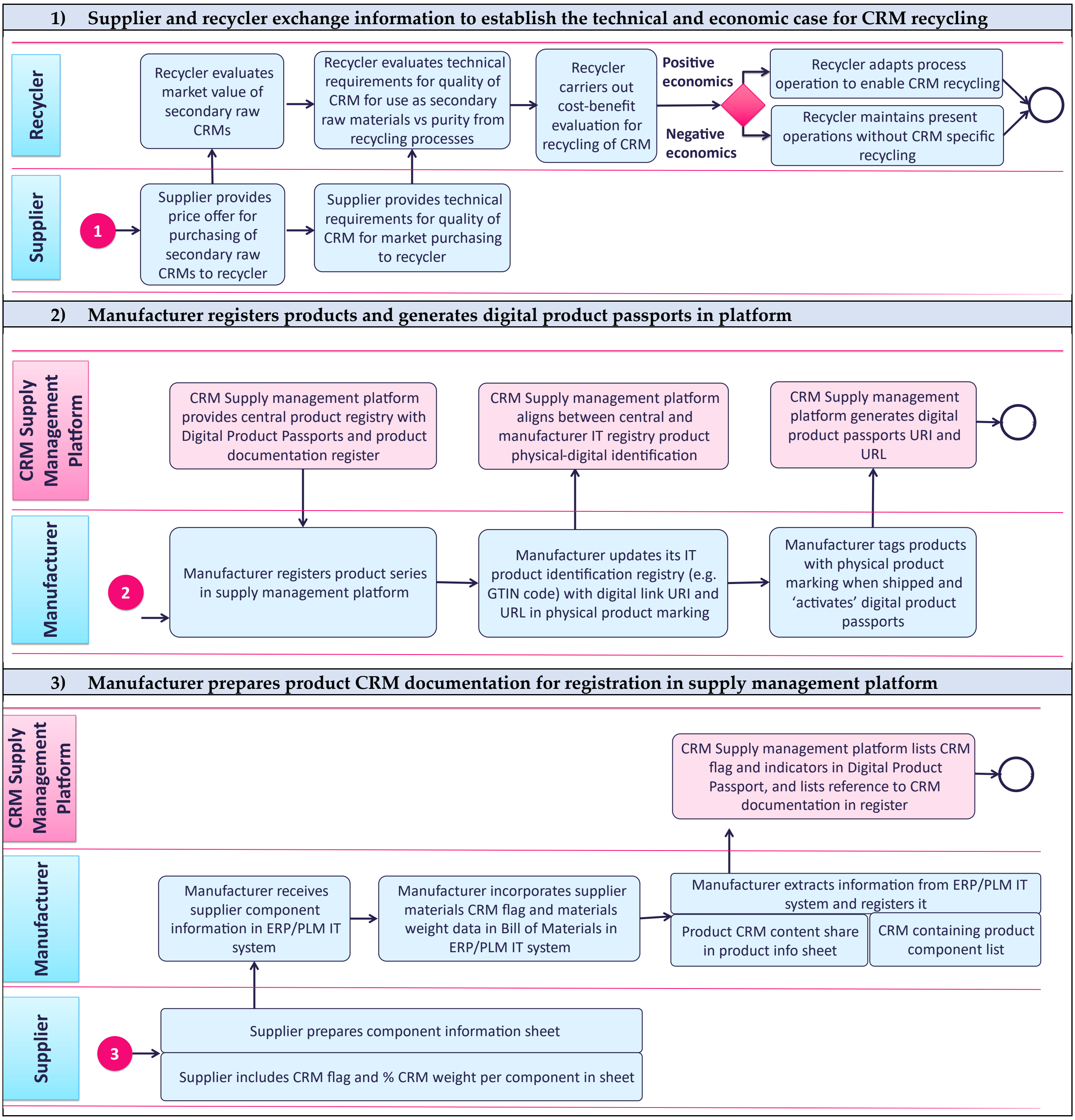
4.3. Information Exchange and Information Processing Requirements

The pain points and needs were studied to evaluate specific information exchanges and information processing approaches for Circular CRM supply management at the individual product level. A total of eleven information exchange and process workflows were defined as presented in Figure 2 that are needed for Circular CRM supply management. In addition, two additional workflows presented in Figure 3 could be introduced to optimise the recovery of components with high-CRM contents using disassembly processes. Two different routes for recycling of CRMs are here taken into account, either by extracting individual high-CRM components which are subsequently sent to a specialised CRM recycling facility, or by shredding the product and recovering the CRMs through sorting, separation and concentration processes across pre-treatment and recycling. Specific recycling technologies are not identified or considered here.

The key processes and exchanges of the Circular CRM supply management system include:

- The exchange between secondary raw materials users (demand) and recyclers (supply) to identify the quality requirements in terms of purity and technical specifications for sales of recycled CRMs, to enable the recycler to carry out a cost-benefit analysis for CRM recycling process's introduction (workflow 1 Figure 2);
- The setup of a Digital Product Passport and product documentation register at product series level in the Circular CRM supply management platform, linked to physical-digital identifiers for purpose of making available product and component CRM content data (workflow 2 Figure 2);
- The preparation of CRM documentation by the manufacturer including a flag based on % CRM content for different types of CRMs for the Digital Product Passport, a linked product CRM information sheet, and a linked product component list identifying high CRM content components (workflow 3 Figure 2);
- The updating of the Digital Product Passport at point of collection and pre-treatment when the product is still intact to update the product life cycle status (workflow 4 and 8 Figure 2);
- The use of the digital product passport CRM content flag per type of CRM by collection companies to separate products with high-CRM and low-CRM content in a relevant grouping of CRMs into different collection bays for further reverse logistics purposes (workflow 5 Figure 2);
- The processing of high-CRM content products by pre-treatment operator when received from the collector as arranged by producer responsibility organisation (workflow 6 Figure 2). Two possible routes are identified:
    - The use of the product component CRM content lists by the pre-treatment operator of products to identify those that should receive specific disassembly efforts to extract particular high content CRM components taking into account high CRM component or material demand, and the follow-up extraction of those components by manual workers for shipment to CRM specialised recyclers (workflow 7 Figure 2);

- ○ The use of the product level CRM content list by the pre-treatment operator to confirm the CRM content of received products for shredding and magnetic and mechanical sorting into batches or heaps with high concentrations of CRM materials (workflow 10 Figure 2);
- The processing of the high content CRM components or of high CRM content material heaps by a recycler specialised in CRM materials processing into secondary raw materials, using further mechanical and/or chemical treatment processes (workflows 9 and 11 Figure 2);



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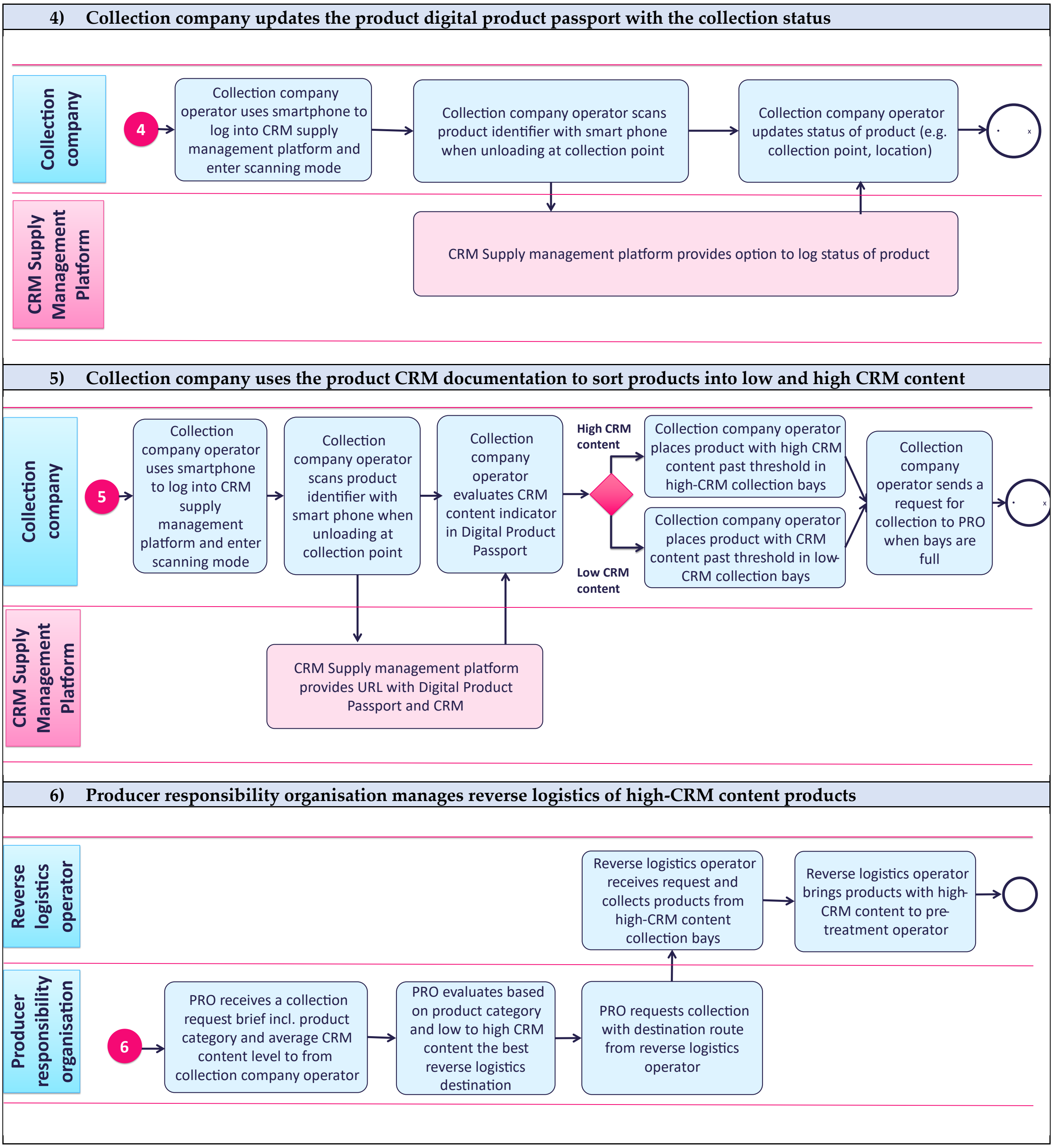

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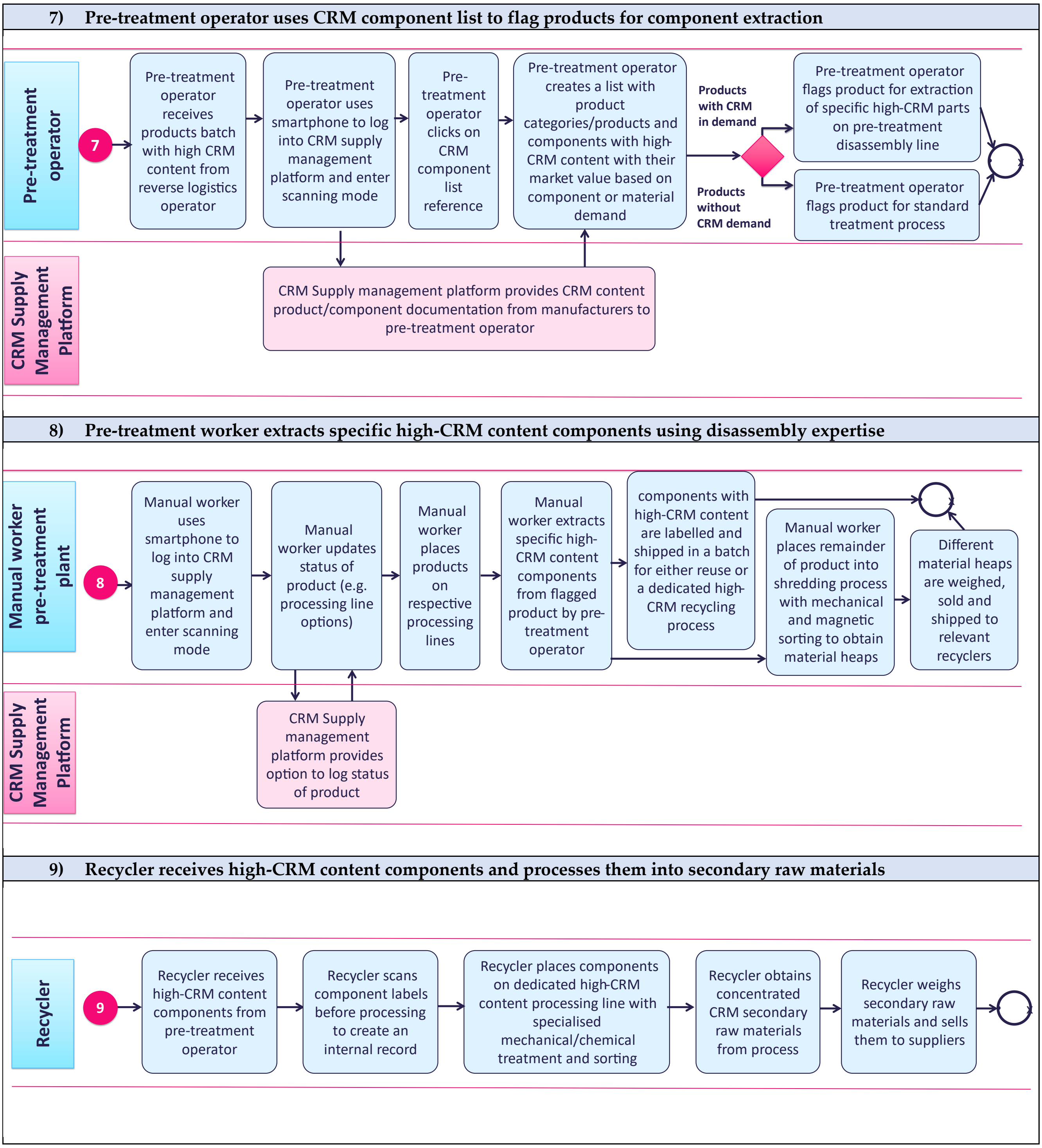

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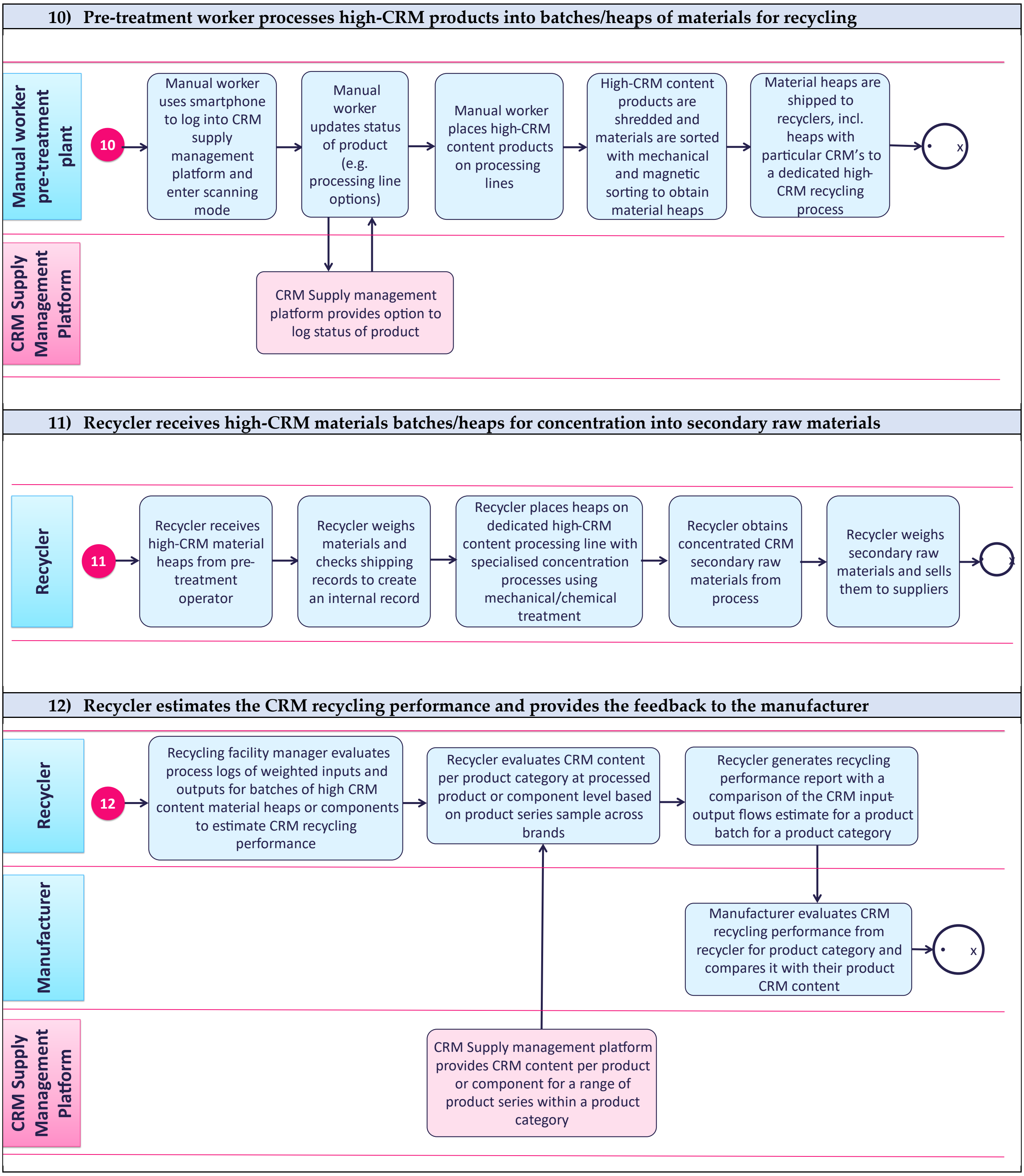

Figure 2. Overview of information exchanges for Circular CRM supply management system.

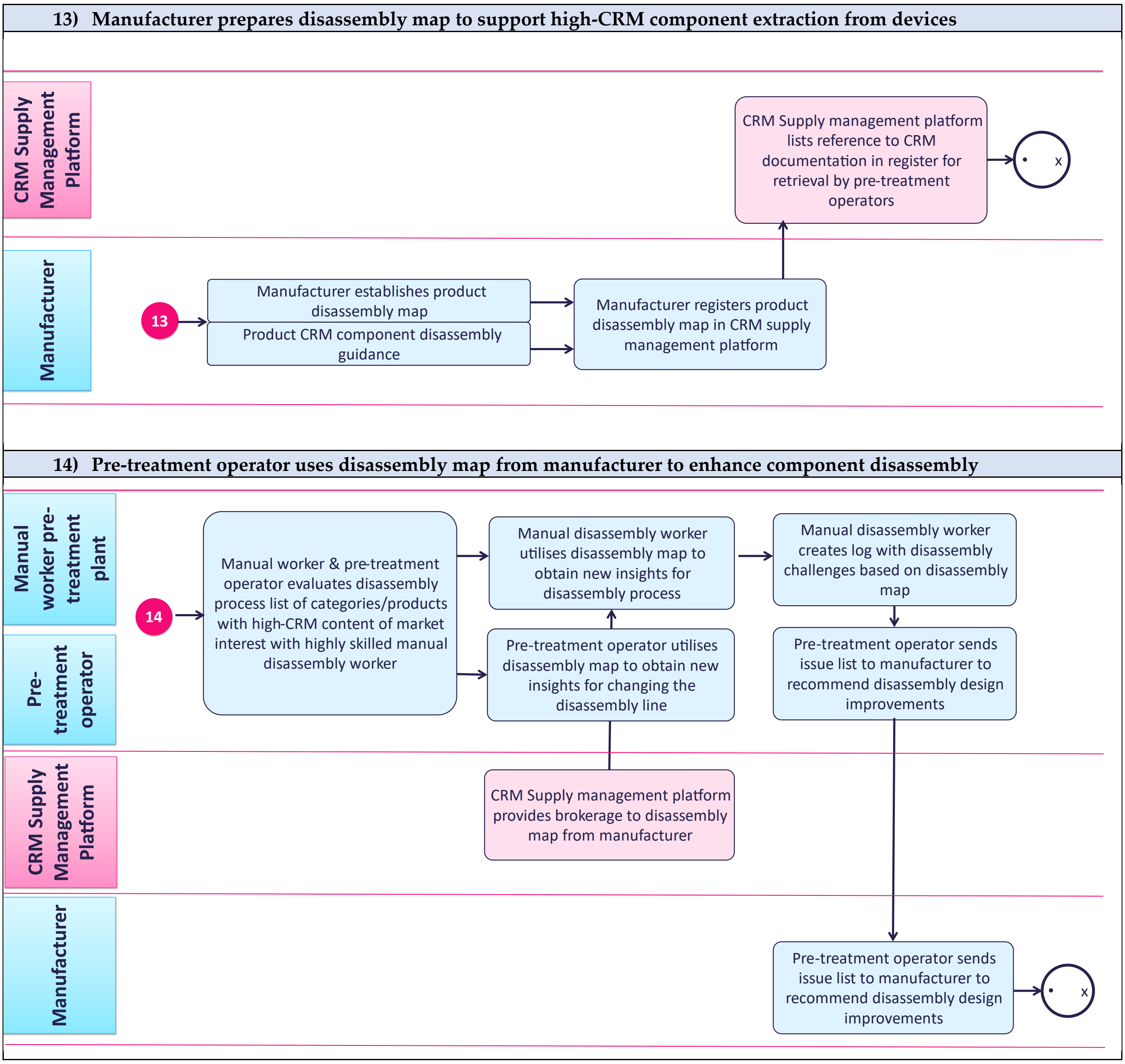

Figure 3. Information exchanges for enhancing disassembly processes for CRM component recovery.

- The feedback loop of CRM recycling performance of products and components into secondary raw materials from recyclers to manufacturers, for purposes of improving product design to enhance recovery and recycling (workflow 12 Figure 2);
- The provisioning of a disassembly map of the product and specific CRM containing components by the manufacturer, with feedback back from the pre-treatment operator to the manufacturer on disassembly issues based on a disassembly log (workflows 13 and 14 Figure 3).

4.4. Circular CRM Supply Management System Architecture

The implementation of information exchanges and processes requires the delivery of a complex software system to manage the generation, processing and sharing of data across product life cycle actors including manufacturers, collectors, pre-treatment operators, recyclers, and potentially also suppliers of product components. The architecture is designed based on an information exchange and brokerage platform, setup to govern exchanges between the IT systems of the providers of information and the IT systems of the consumers of this information connected through the internet.

The standard components of an International Data Spaces information brokerage platform [25] include: a *connector* that sits on the IT systems of both ends that enables standardised processing of the information; a *local data application* that generates or processes the information and feeds it to the connector, either directly or via a local data store; a *meta-data broker* which lists the available connectors and associated information from data providers to initiate transfers; a *data contracts manager* that stores the policies set for exchanging the information; and a *clearing house* which records transactions that have taken place. Additional IT components are needed to increase the level of trust between the parties that exchange information: a *certificate authority* that registers and certifies connectors for permission of brokerage; a *certificate verifier* that for each time a document or dataset is brokered assures the connectors are certified; and a *participant information system* that registers the organisations to increase trust. These three modules together form an identity verification system to ensure that only registered and certified parties from both organisational and IT sides are able to broker information between them.

The circular CRM supply management system requires a number of additional components: a *product series registry* that contains an interface and data store to capture the product category, manufacturer, brand, name and identification numbers such as product ID number and series number; a *Digital Product Passport(s) generator* which provides for an interface and data store to generate the DPPs about individual products that include the CRM product flag and indicators; the meta-data broker can be setup as a *product Meta-data catalogue* that forms the entry point for retrieving the product/component CRM documentation; a *product tag generator* and data store to create the physical-digital linkage to scan the product that enables access to the DPP and product Meta-data catalogue on the internet; a *tag scanning mobile app* for providing user options depending on the user role such as updating the DPP or accessing it directly.

The components of the architecture are shown in Figure 4 in their relationship to each other, and how they would sit in terms of IT servers across information providers, consumers and the circular CRM supply management platform cloud. The user interactions within the architecture are foreseen at three levels: a standard centralized user interface to setup the product model registration and public digital product passport information structures and to verify connectors that are exposed; a decentralized interface at the connector level to setup connectors and associated applications and to provide for data policies that are stored in the data contracts manager, to set access conditions to the provided information through a connector; and a decentralized mobile application interface to scan the product tag to access the Digital Product Passport at the related URL as an entry point. Different decisions-making routes can then be built through the architecture, such as to identify the organization types or roles that can access particular documents through the connector data policies. New applications can be built with a connector to link to the data space to obtain and process available data, and information entry can be made possible from a mobile application that can read the Digital Product Passport or write to it given an authorization procedure to update the product life cycle information. The approach allows for storing data de-centrally at the data provider side enabling data sovereignty, as well as centrally in a Digital Product Passport data-store, and mixing these approaches. It allows for creating visibility on who owns a particular dataset in a structured manner, and logging product life cycle stages with timestamps to enhance product life cycle transparency.

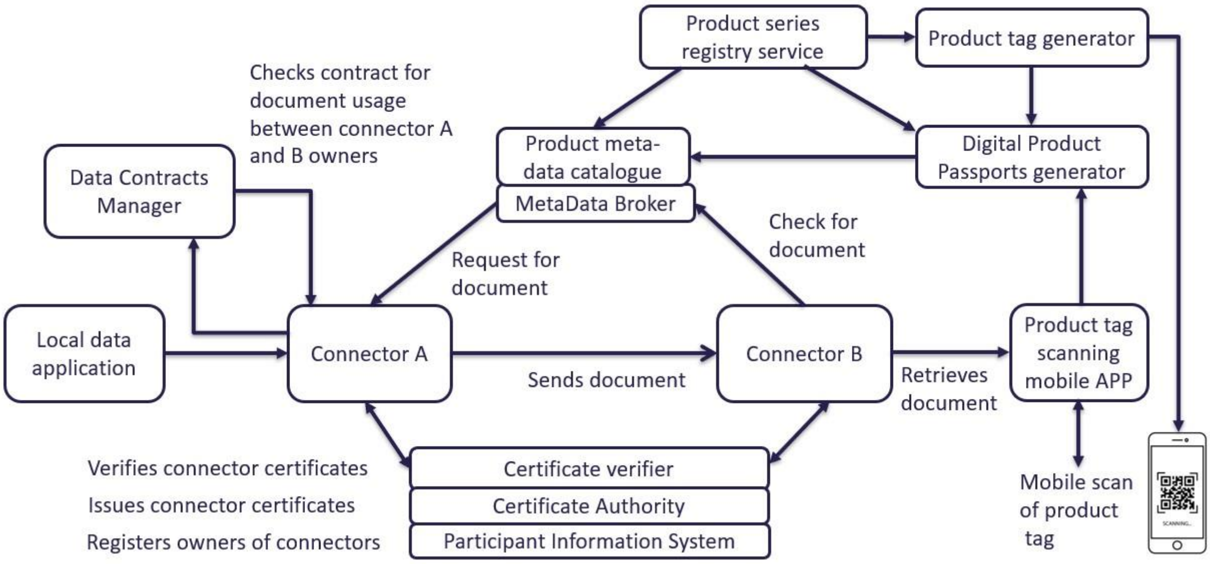

Figure 4. IT architecture of the circular CRM supply management platform using Digital Product Passports based on the International Data Spaces reference architecture.

Another key part of the architecture is the standardisation of the IT approach to information brokerage or information exchange management [25] within the context of Digital Product Passports, as well as the utilisation of standards to govern the structure of information that is exchanged to improve information management. The proposed relevant standards to be applied in this architecture include: IPC-157x to structure the Bill of Materials and to standardise exchanges between suppliers and manufacturers, which is an XML file format standards family [26]; EN 45558:2019 to list the CRM content in mass or mass % at product level based on the standard IEC 62474 for electronic products and its XML format for declaration, and to list which components contain CRM's [27,28]; EN 45554:2020 to inform how to estimate the effort to extract CRM containing components based on the depth of disassembly [29]; and EN 50625:2014 or EN 45555 to inform how to evaluate the CRM recycling performance [27,30]. Finally, for the declaration of CRM recycled content in products, the standard EN 45557:2020 can be used [31]. Key standards of relevance that are still in the development stage include: IEC/CD 82474-1 Material declaration—part 1: General requirements [32], which seeks to extend IEC 62474 for all types of products, and ISO/WD 59040, which seeks to standardise Product Circularity Data Sheets, including recycling materials declarations for products [33]. Additionally, the EN 50625:2013 standard has been evaluated as the best standard in the CEWASTE project standards screening to improve accounting of critical raw materials flows at a recycling plant, by requiring accounting of the inputs and output components and fractions for CRM's across process steps [34].

The architecture for mapping the CRMs by a manufacturer with its supplier in detail, to extract this information into a CRM materials declaration document. To securely broker this document to a pre-treatment operator and a recycler for providing composition data, without any intermediaries having access to the document. To enable retrieving the document using a product tag such as a QR code for decision making and information collection. This includes extracting CRM containing components for re-use purposes and recycling purposes. Traceability of CRM content through material declarations will enable investments in CRM specific recycling systems. Once they are in place, the architecture allows for accounting for the CRM recycling performance and provide this information back with feedback to the manufacturer. This includes information on disassembly performance to extract CRM containing components and the % of CRM content that is recycled. The feedback will help to improve the manufacturer's product from a CRM supply management perspective.

5. Discussion

The paper provides the design of a supply management system and architecture for enabling CRM traceability and management of secondary raw materials supply, at both a strategic and manufacturer specific level. The key aim is to enable information flow about CRMs contained in products at both product level and component level. The reason is to enhance CRM component supply via reuse and reduce the need for virgin component manufacturing. As well as enable the separation and recycling of CRMs to produce secondary raw materials to reduce the need for virgin materials mining. The approach can be used in a similar manner for all types of materials.

Key challenges for setting up such a system relate primarily to the limited incentives at present for manufacturers, how to manage the CRM secondary raw materials extraction for the existing 1.3 billion electrical and electronic products on the EU market that do not have Digital Product Passports [35] and ensuring investments in CRM extraction technologies at recycling plants.

Manufacturers will need to invest in standardising Bill of Materials and associated material declarations, especially on a standalone basis if there is no level playing field. The main benefits accrue to recyclers who will be able to improve the value extracted out of products they already recycle, and by enabling the reselling of reusable CRM containing components. Manufacturers themselves face primarily costs in setting up material declarations, and it is unlikely that a single manufacturer would invest by itself. Legislation can address this by creating a level playing field. The EU commission Ecodesign for sustainable Products Regulation proposal from March 2022 contains the overarching framework for setting up Digital Product Passports per product category within the EU market [17]. The proposal at present fails to mention materials declarations and CRM information for products, however. At the time of writing the EU parliament is providing its viewpoints on the proposal and there is still room for change. If included at a legislative level that materials declarations including CRM content would become mandatory over a given timeframe, this would generate a level playing field for manufacturers on the EU market. Another potential opportunity would be the upcoming revision of the WEEE directive that regulates the proper management and recycling of Waste Electrical and Electronic Equipment.

Another challenge lies in managing the CRMs in appliances that are already on the market and those that will be manufactured until the point that their Digital Product Passports with materials declarations are available. These can be referred to as legacy appliances that lack traceability. One potential solution would be to create approximate material declaration values per product category. There are 51 categories of products for WEEE identified in the UNU-KEYS framework that is recognised as the best available categorisation [36]. These can subsequently be utilised generically and also at individual product level. To this end, a system can be built to generate Digital Product Passports not at the point of manufacturing but at the point of collection from users when products are at the end of their life. A product category specific DPP can be generated enhanced with product model data using existing barcodes and identifiers entered upon collection, with a tag placed upon the product upon collection. The result is traceability from collection to potential testing for reuse and recycling, the use of more generic materials declarations and the possibilities for feedback to the manufacturer from recyclers.

The final challenge is to ensure that the supply management system unlocks sufficient investments in CRM extraction technologies at recycling plants. At present for most CRM's these barely exist with one cause being the lack of available CRM information and the cost of CRM recycling technologies. A large WEEE recycling plant will have an investment capacity in order of magnitude of several hundred thousand euro per year on its own, which means that one to two process technology upgrades are possible every year. The value of extracting specific CRM's, such as cobalt, beryllium or graphite can be calculated if their material flows within a recycling facility can be estimated. This will aid the make-or-break calculations needed to know at what secondary raw material price and purity new process investments are worthwhile. To aid such investments the market for secondary raw materials will need to be strengthened, such as by requiring a % of recycled CRM content in products on the EU market as part of the new Ecodesign for Sustainable Products Regulation. This would result in price increases as it would grow the demand for recycled CRM's. Another option would be by setting a market price floor per tonne for particular CRM's paid through Extended Producer Responsibility schemes under the WEEE directive. This can be based on a contracts for differences price contract, where the buyer pays the seller for the difference to the market price and the price floor if the market price drops below the floor and vice versa. In this context, a manufacturer and a recycler can set up a contract. This can become feasible once product brands can be recognised via Digital Product Passports at a recycler's facility so as to identify company specific products that would fall under the contracts for differences. This would provide for stabilisation of prices to increase investment certainty for a recycler.

6. Conclusions

The paper provides for the conceptual design of a circular supply management system for Critical Raw Materials based on Digital Product Passports. The aim is to enable its implementation to improve the recycling of critical raw materials in the EU so as to reduce import dependencies. The following conclusions can be drawn from the design process:

- Based on a survey with 10 EEE manufacturers and WEEE collection organisations and recyclers it was established that no critical raw materials specific life cycle product/materials information management is in place today among these organisations;
- The core needs evaluated by the 10 organisations to improve critical raw materials reuse and recycling include: improved knowledge about the secondary raw materials market for CRMs for manufacturers; obtaining insights in the CRM content of products for collectors to enable separate collections or pre-sorting of products and potential extraction of CRM containing components; having visibility on the CRM content in incoming flows of products and materials for recyclers to improve the disassembly and pre-treatment before recycling; and feedback from the recycler to the manufacturer on what happens with products during the recycling phase;
- The information processes assessed that a Circular CRM supply management system needs to include: a Digital Product Passport with a documentation register at product series level accessible via physical product tags; CRM contents documentation prepared by the manufacturer with information on the materials content; a list of high CRM content components in the product; a sorting of products with high and low CRM content at the collection stage; a disassembly map of a product from the manufacturer to improve component extraction for reuse/recycling; and feedback on CRM recycling performance of products and components from recyclers to manufacturers.
- The proposed IT infrastructure to implement these information processes is based on a data spaces model that facilitates direct exchanges of documents between two organisations, such as a manufacturer and a recycler, to improve trust and security. A total of 13 IT components are proposed based on the International Data Spaces Association reference brokerage platform. To govern the information exchanges six existing and two upcoming standards are proposed as developed by European and global standardisation bodies.

The technical design and subsequent implementation of the IT infrastructure will be a next step so as to validate the conceptual design of the circular supply management system. As further research directions, techno-economic and business model analyses on the pre-treatment and recycling of critical raw materials are proposed so as to increase the speed of investments in the critical raw material's circular economy.

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