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DECENTRALISED DATA EXCHANGE IN CONSTRUCTION DATA SPACES USING INFORMATION CONTAINERS

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Abstract

The decentralised construction industry is suited for leveraging the Data Space concept. The Information Container for linked Document Delivery (ICDD) specification enables targeted data sharing through dedicated connectors to create secure and interoperable decentralised data ecosystems. This study integrates ICDD containers as queryable web resources within the International Data Spaces (IDS) Reference Architecture Model. The approach is validated in a circular construction case allowing the exchange of multimodal data via the Data Space. Aa marketplace application, acting as a data consumer, retrieves building elements available for reuse from decentralised containers, ensuring secure and standardised exchange.

Introduction

Data and system integration is a cornerstone in Architecture, Engineering, and Construction (AEC) as it streamlines complex workflows and enhances cross-life-cycle data sharing and management. Much of the existing research has focused on open standards, data models, and Common Data Environments (CDEs), which have revolutionised data exchange in the domain. However, while pivotal in centralising project data, CDEs lack the ability to make data easily interoperable across building projects and multiple life cycles, leading to transparency and reliability issues (Jaskula et al., 2024). As such systems are typically designed to address immediate data management needs, they often lack the robustness and scalability for long-term data management, exchange, and reuse. In this regard, such approaches do not fully meet the needs for sustainable asset management, which also requires sustainable digital object management in the long term. Among others, the ambitions and goals related to achieving a circular construction industry call for efficient and seamless reuse of data and objects between projects, assets, asset owners, and systems (Çetin et al., 2022).

The promise of Semantic Web and Linked Data technologies has been significant in this regard. Semantic data modelling, ontologies, and web technologies have enabled both decentralised data management and integration while still fulfilling the need for standardised file-based data sharing in the construction domain whenever necessary (Werbrouck et al., 2023; Senthilvel et al., 2021). In this relation, Information Containers for Linked Document Delivery (ICDD) have been designed to bridge the gap between traditional document-based workflows and the interconnected data-centric workflows envisioned by the Semantic Web (Hagedorn et al., 2025, 2023b). Besides enabling targeted data sharing across heterogeneous data sources and systems in a portable manner, ICDD also allows semantic annotation and enrichment of data with meaningful metadata for better discovery and reasoning based on defined relationships between the contents of the container (typically relying on the Resource Description Framework (RDF) (Hagedorn et al., 2023a)). This also includes provenance metadata about the included documents and data, such as source, creation time, and modifications. As such, ICDD provides a step in the right direction compared to, e.g., CDEs, as the latter typically pose limitations when it comes to metadata management or integration of vocabulary providers, e.g., buildingSMART Data Dictionary (bSDD). However, ICDDs also do not utilize the full potential of semantic data modelling and web technologies, as containers have limitations when it comes to distributed data management. To live up to the needs and requirements for digital life cycle information management, ICDD would need to be endowed with capabilities enabling decentralised (live) data sharing.

The state-of-the-art in Building Information Modelling (BIM), Digital Twins (DTs), and Asset Information Management (AIM) points to the importance of static and dynamic data and system integration using, among others, uniform terminology, scalable web technologies and protocols, and secure data access control mechanisms in digital infrastructure development (Chamari et al., 2023). However, standard approaches to data sovereignty, provenance, and transaction governance are still in their infancy or are not covered in detail in existing architectures.

As a relatively recent concept, Data Spaces emphasize decentralisation, security, access control, sovereignty, and interoperability in managing and exchanging data between *Data Providers* and *Data Consumers* using trusted connectors and governance frameworks (Curry et al., 2022; Nagel and Lycklama, 2021). By relying on standard formats, protocols, and ontologies, Data Spaces aim to enable seamless and trusted data sharing and integration across systems, where data owners retain control over their data. While the implementation of Data Spaces for exchanging dynamic data by directly connecting to exposed endpoints has seen several implementations in various domains and use cases (Berkhout et al., 2022; Pretzsch et al., 2022), the question concerning their relevance for construction, particularly when exchanging static data packages, remains.

Therefore, this study aims to explore the potential for creating synergies between the concepts of ICDD and Data Spaces for construction to enable targeted information exchanges that live up to the decentralisation and trustworthy data exchange visions described above. Building on the Reference Architecture Model provided by the International Data Spaces Association (IDSA), the paper presents a proof-of-concept for exchanging multimodal data via a Data Space by establishing a trusted connection between an ICDD Application Programming Interface (API) as a provider of information about building elements available for reuse, and a circular construction marketplace web application as a *Data Consumer*.

The remainder of this paper is organised as follows. Sections *Information Containers in AEC* and *Data Spaces in AEC* present the related works in the area of information containers and data spaces, including existing challenges and limitations. Section *Concept & Implementation* outlines the methodology adopted in the study and the conceptual system architecture. Section *Case Study: Circularity Marketplace* demonstrates the implementation using a circular construction case study and discusses the results. Finally, Section *Conclusion* concludes the paper and highlights future work.

Information Containers in AEC

While referencing or extending the Industry Foundation Classes (IFC) schema for cross-domain heterogeneous, distributed information does not increase interoperability between applications (Pauwels, 2014), a solution could involve maintaining documents and models in their original interoperable, interpretable format and linking them through a metadata-level approach. The container-based data exchange in BIM is embodied in the Information Container for Linked Document Delivery (ICDD), formalised as ISO 21597-1 (2020). This international standard is based on the Multi-Model Container (MMC) (Fuchs et al., 2011) and COINS container (van Nederveen et al., 2010) approaches. ICDD is a ZIP64 file (*.icdd) that efficiently exchanges diverse data by uniquely identifying documents with URIs and linking them using Semantic Web technologies. These linksets support connections across models, formats, and domains. The ICDD standard prescribes a container structure that includes an *index.rdf* file and three main folders: *Ontology resources*, *Payload documents*, and *Payload triples*. *Ontology resources* contain RDF-based files defining container, linkset, and extended linkset ontologies from the ICDD standard and additional ontologies from describing the content of the container. *Payload documents* host internal files, and *Payload triples* store RDF/XML linksets describing document interrelations (ISO 21597-1, 2020).

A web-based implementation of the ICDD as a CDE has been introduced by Hagedorn et al. (2023a). The authors argue that despite the zip-packaged format, a web-based implementation is the next logical step when utilizing the ICDD for information exchange in the construction domain, since the fundamental schemes are already employing web and Semantic Web technologies, e.g., RDF for metadata management and the SPARQL query language for retrieving information from containers. Thus, they propose a software architecture and a web-based implementation that is demonstrated using a transportation infrastructure asset management use case. Senthilvel et al. (2021) implemented the ICDD as a micro-service and pointed out the advantages of using ICDD in a web-based context. These include accessibility, interlinking, and querying based on metadata, also between multiple containers. Werbrouck et al. (2023) further investigated federated BIM in web-based collaboration using Semantic Web technology and ICDD as part of the ConSolid ecosystem.

The ICDD is designed to streamline and enhance construction data management. By establishing a unified format for storing and sharing information, ICDD helps reduce the discrepancies between different data sources (Hagedorn et al., 2023c). This consistent structure minimizes errors in interpretation and use, ensuring that all parties work with the same information base. ICDD ensures data longevity by storing it in a non-proprietary format.

The current limitations of the ICDD standard present challenges for efficient web-based data linking and information management in construction projects. In previous research, the ICDD standard was analyzed for its drawbacks (Hagedorn et al., 2023b). Despite Linked Data principles aiming to facilitate seamless data integration, the restrictive linking mechanisms of ICDD hinder effective external data linkage. The lack of standardised access policies and limited web-based container allocation methods further complicate data sharing. Moreover, as a ZIP-based format, ICDD falls short of web resource capabilities, remaining primarily a local file system.

Data Spaces in AEC

Concepts and definitions

The *Data Space* concept (Figure 1) is promising to overcome some of the limitations of the ICDD standard. A *Data Space* facilitates trustworthy and standardised data sharing and exchange between multiple stakeholders in distributed data ecosystems. Multiple initiatives address the development of Data Space definitions and frameworks, including the International Data Spaces Association (IDSA), the Data Spaces Business Alliance (DSBA), the OPENDEI project, and GAIA-X. Some initiatives of a similar nature tried to map ideas of those *Data Space* concepts to the construction industry, including the DataPLACE project (Mirarchi et al., 2021) and the DigiChecks project (Gil et al., 2024). Those initiatives typically fo-

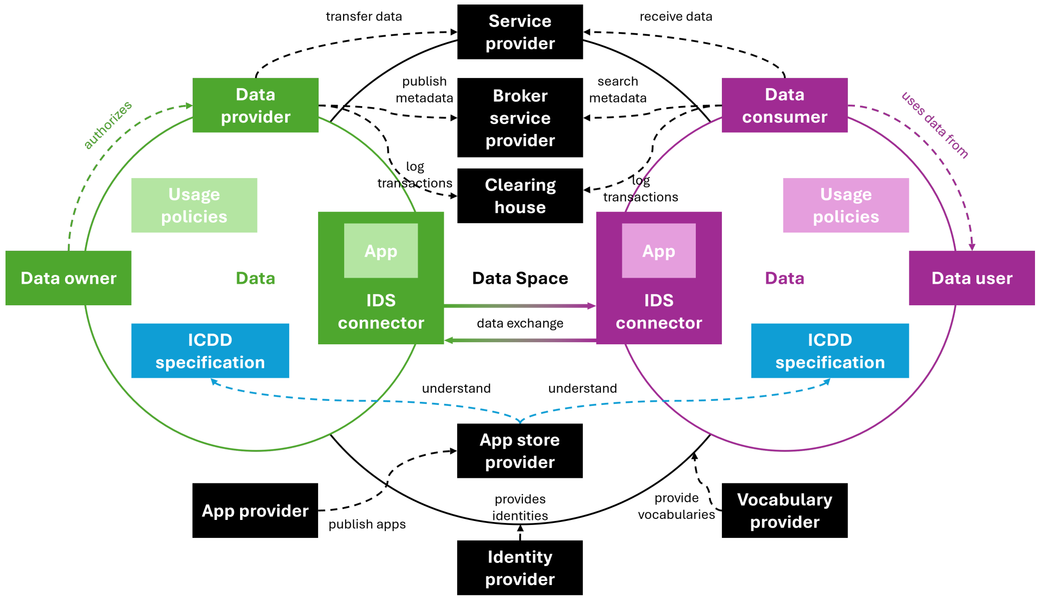

Figure 1: Conceptualization of the Dataspace based on the ICDD specification: Provider including connector (left, green), Consumer including connector (right, purple), exchange mechanisms and data space components (center, black)

cus on theoretical or conceptual representations of *Data Spaces*. The practical implementation of those ideas remains limited. For instance, van Zandwijk (2024) focused on the development and testing of a functional user interface to an AECO *Data Space*.

The OPENDEI project resulted in a position paper by Nagel and Lycklama (2021) presenting principles for the creation of *Data Spaces*, namely: i) data sovereignty, ensuring self-determination of ones data, ii) data level playing field, ensuring a level playing field and low entrance barriers for new companies, iii) decentralised soft infrastructure, aiming for a collection of interoperable infrastructure that follows a set of agreements on functional, technical, operational and economic principles, and iv) public-private governance, aiming for collaborative governance of the *Data Spaces* where data users, providers, and technological partners have responsibilities and a feeling of ownership.

Nagel and Lycklama (2021) also mention four technical challenges in the *Data Space* initiative, related to the data-sharing lifecycle, data ownership, data provenance, and challenges related to the decentralised architecture of *Data Spaces*. Next to mentioning decentralisation and digital sovereignty, Scerri et al. (2022) add sharing by design, veracity, security and privacy protection to the debate. There are obvious challenges of a non-technical nature related to the domains of business and organisation, legal, economics, and challenges of a more regional nature (Nagel and Lycklama, 2021; Scerri et al., 2022). Providing answers to the non-technical challenges is out of scope for this paper.

The IDSA translated potential answers to those challenges into their RAM 4.0, a reference architecture that aims to enable decentralised data sharing in *Data Spaces*. This architecture contains various core components, including connectors (communication servers that deal with sending and receiving data according to predefined specifications), metadata broker (a repository that deals with metadata of the data sources in the Data Space), clearing house (the component that deals with (monetary) transactions and provides clearing and settlement services), vocabulary hub (server providing vocabularies - or ontologies - that enable interoperability between various components and content in the data space), and an app store (that provides end-users with applications that add additional functionalities to the data space architecture). While the IDSA RAM 4.0 provides a global architecture for *Data Spaces*, it does not cover technical solutions for each component. Nagel and Lycklama (2021) suggested that *Data Spaces* will be, to some extent, sector-specific, and van Zandwijk (2024) argued that an AECO *Data Space* could only function if it follows AECO-specific standards such as ISO 19650.

Communication infrastructure and data exchange

Fundamentally, the data exchange infrastructure in *Data Spaces* relies on establishing a secure communication following formalised data exchange policies and exchange of information using trusted protocols and connectors. In other words, a *Data Provider* and a *Data Consumer* exchange data while adhering to the principles of secure communication, data sovereignty, and policy enforcement. The connectors in data spaces communicate through a combination of standardised protocols (e.g., HTTP, MQTT, RESTful APIs, etc.), data models (e.g., JSON, XML, etc.), and middleware to ensure secure, efficient, and interoperable data sharing where multimodal data (e.g., text, images, objects, etc.) can also be provided in a single (multipart) response. One example is the IDS Multipart Protocol, which is typically applied in scenarios where data needs to be transferred in a segmented for-

mat, such as in the case of big data or when multiple components need to be exchanged securely between different systems in a distributed network.
As such, connectors use metadata brokers (or registries) to discover other services or participants in the data space. In this context, metadata includes information on the available datasets, APIs, and the corresponding access conditions. In a nutshell, the discovery, communication, and exchange workflow comprises the following steps:

1. Discovery: Connector A (*Data Consumer*) sends a query to the metadata broker to discover a suitable data source and receives a response on the available endpoints, data types, and access policies;

2. Handshake: Connector A (*Data Consumer*) and Connector B (*Data Provider*) establish a secure connection using security, authentication and authorisation protocols (e.g., X.509 certificate, OAuth 2.0, OpenID Connect);

3. Negotiation: Data usage policies are exchanged and agreed upon (e.g., data retention period, maximum data request frequency, prohibited uses, etc.);

4. Data Transfer: Data is exchanged based on the agreed standards and formats;

5. Acknowledgment: The *Data Consumer* receives a notification for successful/failed transfers, completing a transaction log;

Concept & Implementation

The proposed solution for the technical implementation of *Data Spaces* in the AEC industry is to place the ICDD specification inside the IDSA RAM 4.0 (see Figure 1). The IDSA RAM 4.0 already specifies mechanisms for shared vocabulary, metadata management, and access control but does not explicitly state domain-specific implementations of these. Instead, it focuses on IoT data rather than larger static files from the construction domain, which are interrelated and their management across a long lifecycle. ICDD can supplement the RAM principles, specifically when transferring use-case-specific static information and provide corresponding metadata schemes and linkage. The figure shows that the providing *IDS connector* (green) and the consuming *IDS connector* (purple) conduct the data exchange within the *Data Space* (black) based on the ICDD specification that is commonly understood. A variety of applications, provided by *App store providers*, can be built on top of the data that is exchanged using this ICDD specification, as long as those applications are able to understand the internal structure of the ICDD container. Although this paper does not research potential Vocabulary providers in depth, and the IDSA RAM 4.0 does not specify preferences for such providers in the AECO industry, it is believed that the buildingSmart Data Dictionary could serve as such a provider in AECO *Data Spaces*, as it enables using vocabularies both in RDF graphs and in IFC files, and thus bridges semantics between those two. The following subsections provide a detailed discussion of the implementation of the *Data Provider* and the *Data Consumer*.

Connector for the ICDD API as a Data Provider

The ICDD Platform, as proposed in Hagedorn et al. (2023b), is the main component of the *Data Provider* (see Figure 2). The platform serves ICDD containers and their contents via a documented OpenICDD API[1]. In this research, the OpenICDD interface should be extended for viable access to the ICDD Platform via an IDS connector in the *Data Space*. The extension should cover exchang-

[1] https://philhag.github.io/open-icdd/, last accessed: 28.01.2025

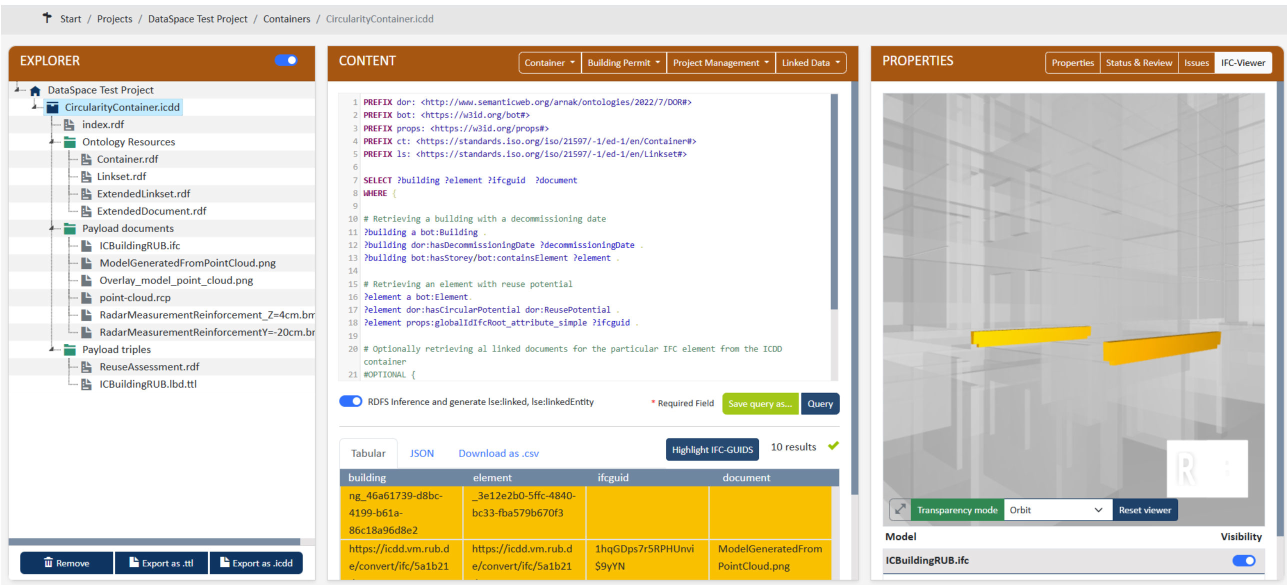

Figure 2: ICDD Platform containing the model of a decommissioned building and the respective information on reuse of elements

ing ICDD containers with granted access between the *Data Provider* and a *Data Consumer* that can be filtered using SPARQL queries. Besides exchanging the ICDD container, it should provide metadata queried via SPARQL at the extended route. Providing a singular access point for consumers, the new query route implemented in a generalised way serving an `multipart/byteranges` result that can be composed of the metadata and the ICDD container or respective models. The endpoint therein retrieves ICDD containers or IFC models that a logged-in user is authorised to access and that deliver results for the provided query input.

The endpoint expects an `HTTP POST` request according to the SPARQL HTTP Protocol (Feigenbaum et al., 2013) Section 2.1.3 and accepts an `application/sparql-query` content as a body. In the ICDD Platform, the request is processed, and the query is executed for each accessible project while the SPARQL results are grouped by the containers. The `multipart/byteranges` response content type is used to return multiple ranges of data from a resource, such as when serving partial content for file downloads or streaming, with each range encapsulated in its own MIME boundary. Each part in the response includes its own Content-Type and Content-Range headers, allowing clients to process the specific data segments independently.

To integrate the ICDD Platform into the *Data Space*, we utilize the open-source Trusted Connector[2] implementation provided by Fraunhofer Institute for Applied and Integrated Security (AISEC). The Trusted Connector is an open-source implementation designed to ensure secure and trusted data exchange in Industrial Data Space environments that runs, for instance, in a Docker container. It provides a modular and extensible architecture, enabling the integration of secure communication, data governance, and compliance features tailored to various industrial use cases. In the Trusted Connector implementation of AISEC, routing is predefined using Apache Camel[3], which enables flexible and programmable data flows between endpoints. Users can define Camel routing rules using domain-specific languages, such as XML or Java, to specify how messages are processed, transformed, and forwarded across connected systems.

The ICDD is set up with a Trusted Connector supporting the IDS Multipart Protocol using the Apache Camel context as provided in Listing 1. In this implementation, a */query* path is exposed by the connector, which is forwarded to the OpenICDD API. While the connectivity is tested, the trust and identity mechanisms of the Trusted Connector are not yet considered in this paper and will be explored in future work where usage control with the IDSCP2 is implemented. Based on this implementation, the connector can be utilised for providing data from ICDD containers in a *Data Space*.

[2]https://github.com/Fraunhofer-AISEC/trusted-connector, last accessed: 14.01.2025

[3]https://github.com/apache/camel, last accessed: 28.01.2025

Marketplace App as a Data Consumer

A novel web application is built that functions as a *Data Consumer* in this project. The app is built on top of the LBDviz app of Donkers et al. (2023), which enables interaction with RDF graphs through a web-based IFC viewer. Access to the ICDD container is secured through OpenAPI 3.0 Bearer authentication. The application, therefore, first sends a request to retrieve a Bearer token to the ICDD Platform. After retrieving the Bearer token, it uses this token in the Authorization header of the HTTP request that retrieves the ICDD data. This request returns data encoded using multipart encoding, where the body contains multiple files or data with different content types, delineated by a boundary string. The response of the HTTP request is, therefore, separated using a multipart decoder based on the content types of each part of the body. ZIP files use a specific content type value and can, therefore, be directly extracted and stored in a folder structure identical to the ICDD container sent by the ICDD Platform. The application first loads the IFC file(s) in the ICDD container using the JavaScript libraries provided by ThatOpenCompany[4]. These libraries convert the IFC file(s) to web geometry using Three.js (so that the app can show the 3D model in a viewer) and store the non-geometric IFC data in JSON, including the GlobalId's. Those GlobalId's are also stored in the RDF graph of the building, and can therefore be used to communicate between objects in the 3D viewer and the RDF graphs in the ICDD container. As other (non-RDF) files in are linked via the ICDD specification, this principle builds on top of the connected data concept (Donkers et al., 2024), linking non-RDF data such as CSV or PNG files to nodes in the linked building data graph.

Case Study: Circularity Marketplace

To test the concept developed in this study, the decommissioning of two complex office buildings is analyzed for the reusability of concrete elements from the 1960s as part of

[4]https://github.com/ThatOpen, last accessed: 28.01.2025

```xml
<camelContext xmlns="http://camel.apache.org/schema/spring">
    <restConfiguration scheme="http" component="jetty"
          host="127.0.0.1" port="80" bindingMode="off" />

    <!-- REST Endpoint -->
    <rest>
        <post path="/query">
            <to uri="direct:sendIcddQuery" />
        </post>
    </rest>

    <!-- Main Route - sendIcddQuery -->
    <route id="sendIcddQuery">
        <from uri="direct:sendIcddQuery" />
        <setBody>
            <simple>${body}</simple>
        </setBody>
        <setHeader name="Content-Type">
            <constant>application/sparql-query</constant>
        </setHeader>
        <setHeader name="Authorization">
            <simple>Bearer ${authToken}</simple>
        </setHeader>
        <log message="Received SPARQL query: ${body}" />
        <to uri="https://icdd.vm.rub.de/dev01/api/v1/query" />
        <log message="Return results: ${body}" />
    </route>
</camelContext>
```

Listing 1: Apache Camel Routing Configuration inside the trusted connector

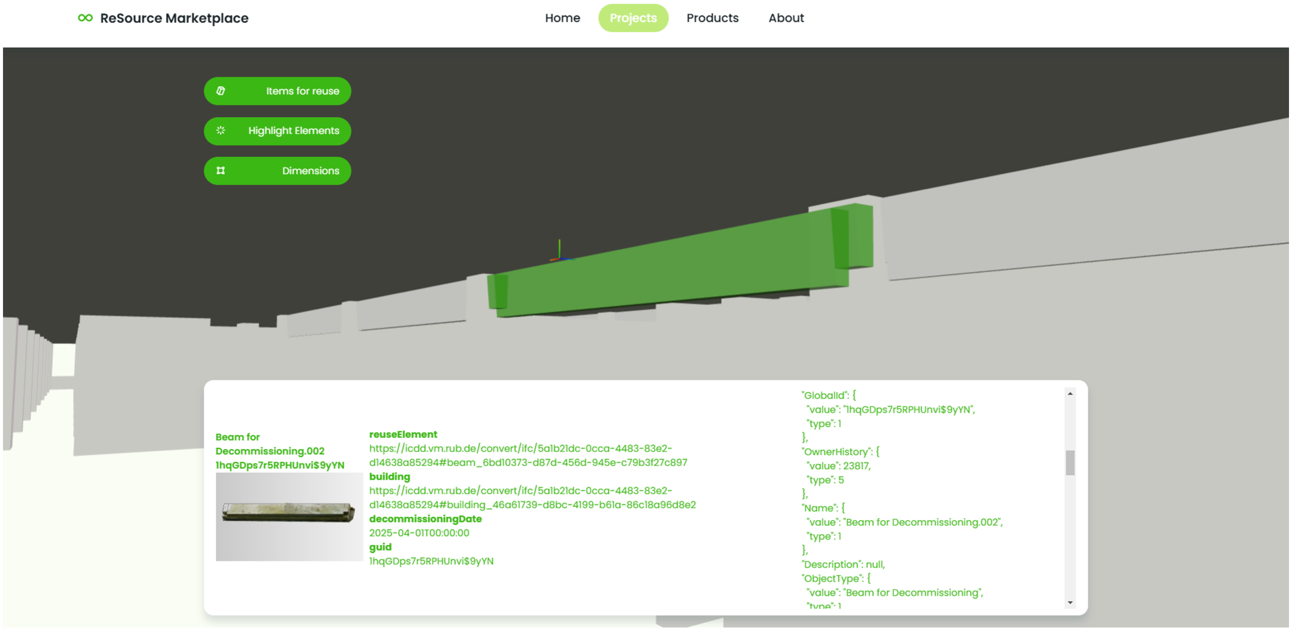

Figure 3: Highlighting a reuse element in the ReSource Marketplace

Figure 4: Case study building on the university campus

the Collaborative Research Center (CRC) 1683 at the Ruhr University Bochum (RUB) (see Figure 4). The data from the two buildings, retrieved through laser scanning for retrospective modelling and non-destructive testing methods for assessing the elements' characteristics, is stored decentralised in ICDD containers. Figure 4 shows concrete beam elements that are employed within this case study to be integrated into the marketplace app.

The developed centralised marketplace app (see Figure 3) is capable of retrieving information from multiple decentralised ICDD containers distributed across various locations. This retrieval process is facilitated through the use of SPARQL queries, enabling the collection of relevant files and associated metadata. The multipart result mechanism and the linkset structure of ICDD are employed to extract detailed information on available elements that can be reused, thereby ensuring efficient data integration and access. The original data in the ICDD container is

```
PREFIX ct: <https://standards.iso.org/iso/21597/-1/ed-1/en/Container#>
PREFIX ls: <https://standards.iso.org/iso/21597/-1/ed-1/en/Linkset#>
PREFIX dor: <http://www.semanticweb.org/arnak/ontologies/2022/7/DOR#>
PREFIX bot: <https://w3id.org/bot#>
PREFIX props: <https://w3id.org/props#>

SELECT ?building ?element ?ifcguid  ?document
WHERE {

# Retrieving a building with a decommissioning date
 ?building a bot:Building .
 ?building dor:hasDecommissioningDate ?decommissioningDate .
 ?building bot:hasStorey/bot:containsElement ?element .

# Retrieving an element with reuse potential
?element a bot:Element.
?element dor:hasCircularPotential dor:ReusePotential .
?element props:globalIdIfcRoot_attribute_simple ?ifcguid .

# Optionally retrieving al linked documents for the particular IFC
        element from the ICDD container
OPTIONAL {
  ?linkElement ls:hasIdentifier/ls:identifier ?ifcguid .
  ?link ls:hasLinkElement ?linkElement .
  ?link ls:hasLinkElement ?otherLinkElement .
  ?otherLinkElement ls:hasDocument/ct:name ?document.
   FILTER(?linkElement!=?otherLinkElement )
 }
}
```

Listing 2: SPARQL query for retrieving semantic description of reusable elements and their attached documentation

structured as presented in Figure 2. The RDF graphs in the ICDD container are enriched with information on the reuse potential of elements by reusing the Decommissioning and Reuse Ontology (DOR) developed by Akbarieh et al. (2023), which is available through the bSDD.

The SPARQL query in Listing 2 is sent as an HTTP POST request to the *Data Provider* to retrieve elements with their reuse potential using the DOR ontology. It specifically queries the building's *dor:hasDecommissioningDate* and the elements' *dor:ReusePotential*, as those are later used to determine which elements are available for reuse in the ReSource Marketplace app. The SPARQL query reuses the ICDD vocabularies to retrieve non-RDF data associated with those elements, such as photos or point clouds. The GUIDs of elements are queried to enable interaction with the IFC model. The ReSource Marketplace highlights the relevant elements in the 3D model, and visualizes contextual information, such as images and point clouds, data from the RDF graphs, and data from the IFC file.

The use case demonstrated that the integration of the ICDD specification into the Data Spaces architecture enables decentralised data exchange to a centralised marketplace. Buildings are decentralised, as are their data, however, an end user should rely on a centralised platform to, for example, find circular construction objects. The ICDD specification is able to capture the decentralised data and its metadata in a package, while the Data Spaces concept is able to manage the data exchange, including usage policies, authentication, and the logging of transactions and metadata. Combining those two concepts provides a solution to the need for a domain specific solution for Data Spaces, as suggested by Nagel and Lycklama (2021).

Conclusion

Data Spaces have shown significant potential for enabling decentralised, secure, and interoperable data ecosystems in various domains (e.g., energy, mobility), especially in the context of real-time exchange of dynamic data. However, their potential for construction and the extent to which they can support not only dynamic but also static data exchanges remain unexplored.

This paper relies on the IDS Reference Architecture Model and presents a concept implementation for employing ICDD containers as a data scheme for exchanging multimodal construction data between *Data Providers* and *Data Consumers* in a construction *Data Space*. The concept proposes the integration of ICDD-based data exchange via connectors in the *Data Space*, thereby extending the OpenICDD REST interface. The concept is implemented and tested in a case study of a circular construction marketplace for reusable concrete elements that retrieves data about available elements and their properties from decentralised information containers based on SPARQL queries. This approach enables more efficient and standardised data exchange in the construction industry, fostering interoperability between diverse stakeholders and systems. The data is provided where the physical elements are provided, at the stakeholder's sovereignty. By leveraging decentralised information containers, it supports circular economy principles, such as the reuse of construction materials, and enhances digital collaboration in data-driven construction processes.

For a full implementation of the IDS Reference Architecture Model, components must be designed and implemented in a context-dependent and domain-specific manner, for which the presented paper provides one possible solution. The challenges arising from the large number of files and file versions typically exchanged in the construction domain influence scalability and practical implementation, requiring dedicated information management strategies alongside technical implementation. How these files connect to vocabularies and what the role of the vocabulary hub in Data Spaces is has still to be determined, for which this study bsDD was presented as a possible vocabulary provider. Future work should also investigate whether it is the best possible implementation for both RDF and non-RDF data. Finally, further implementations must also consider digital identities for managing role-based access as part of the policy-driven data exchange.

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References

Akbarieh, A., Teferle, F. N., and O'Donnell, J. (2023). Semantic Material Bank: A web-based linked data approach for building decommissioning and material reuse. In ECPPM 2022 - eWork and eBusiness in Architecture, Engineering and Construction 2022, pages 69–76. CRC Press, London.

Berkhout, V., Frey, C., Hertweck, P., Nestle, D., and Wickert, M. (2022). Energy Data Space, pages 329–341. Springer International Publishing, Cham, Switzerland. DOI: 10.1007/978-3-030-93975-5_20.

Chamari, L., Petrova, E., and Pauwels, P. (2023). An end-to-end implementation of a service-oriented architecture for data-driven smart buildings. IEEE Access, 11:117261–117281. DOI: 10.1109/ACCESS.2023.3325767.

Curry, E., Scerri, S., and Tuikka, T. (2022). Data Spaces: Design, Deployment, and Future Directions, pages 1–17. Springer International Publishing, Cham, Switzerland. DOI: 10.1007/978-3-030-98636-0_1.

Donkers, A., Janssen Steenberg, M., and Pauwels, P. (2024). Connecting object data in natural stone renovation projects. In Proceedings of the 2024 European Conference on Computing in Construction (EC3). DOI: 10.35490/EC3.2024.249.

Donkers, A., Yang, D., de Vries, B., and Baken, N. (2023). A visual support tool for decision-making over federated building information. In Computer-Aided Architectural Design. INTERCONNECTIONS: Co-computing Beyond Boundaries, Cham. Springer Nature Switzerland. DOI: 10.1007/978-3-031-37189-9_32.

Feigenbaum, L., Williams, G. T., Clark, K. G., and Torres, E. (2013). SPARQL 1.1 Protocol: W3C Recommendation 21 March 2013.

Fuchs, S., Kadolsky, M., and Scherer, R. J. (2011). Formal Description of a Generic Multi-Model. In 2011 IEEE 20th International Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises, pages 205–210. IEEE. DOI: 10.1109/WETICE.2011.34.

Gil, G., Diez, F. J., Romero, R., Lazaro, I., and Fernandez, I. (2024). Construction Data Space for Building Permit Management. In Proceedings of the 2024 European Conference on Computing in Construction, Computing in Construction. European Council for Computing in Construction. DOI: 10.35490/EC3.2024.268.

Hagedorn, P., Liu, L., König, M., Hajdin, R., Blumenfeld, T., Stöckner, M., Billmaier, M., Grossauer, K., and Gavin, K. (2023a). BIM-enabled Infrastructure Asset Management using Information Containers and Semantic Web. ASCE Journal of Computing in Civil Engineering, 37(1). DOI: 10.1061/(ASCE)CP.1943-5487.0001051.

Hagedorn, P., Pauwels, P., and König, M. (2023b). Semantic Rule Checking of Cross-Domain Building Data in Information Containers for Linked Document Delivery using the Shapes Constraint Language. Automation in Construction, 156. DOI: 10.1016/j.autcon.2023.105106.

Hagedorn, P., Petrova, E., and König, M. (2025). A System-of-Systems Approach for Deploying Containerized Construction Digital Twins using Linked Data. In Advances in Information Technology in Civil and Building Engineering: Volume 1: Modeling and Scheduling, Lecture Notes in Civil Engineering, pages 478–491. Springer. DOI: 10.1007/978-3-031-84208-5_36.

Hagedorn, P., Senthilvel, M., Schevers, H., and Verhelst, L. B. (2023c). Towards usable ICDD containers for ontology-driven data linking and link validation. In Proceedings of the 11th Linked Data in Architecture and Construction Workshop (LDAC2023). CEUR Workshop Proceedings.

ISO 21597-1 (2020). Information container for linked document delivery: Exchange specification - Part 1: Container. International Organization for Standardization, Geneva, Switzerland, 1 edition.

Jaskula, K., Kifokeris, D., Papadonikolaki, E., and Rovas, D. (2024). Common data environments in construction: state-of-the-art and challenges for practical implementation. Construction Innovation. DOI: 10.1108/CI-04-2023-0088.

Mirarchi, C., Naville, N., David, A., Pastorelly, N., and Zarli, A. (2021). Toward a Reference Architecture Framework for the development of interoperable construction digital platforms in Europe. Proceedings of the Conference CIB W078 2021.

Nagel, L. and Lycklama, D., editors (2021). Design Principles for Data Spaces: Position Paper. International Data Spaces Association, Dortmund, 1 edition. DOI: 10.5281/ZENODO.5244997.

Pauwels, P. (2014). Supporting Decision-Making in the Building Life-Cycle Using Linked Building Data. Buildings, 4(3):549–579. DOI: 10.3390/buildings4030549.

Pretzsch, S., Drees, H., and Rittershaus, L. (2022). Mobility Data Space, pages 343–361. Springer International Publishing, Cham, Switzerland.

Scerri, S., Tuikka, T., de Vallejo, I. L., and Curry, E. (2022). Common European Data Spaces: Challenges and Opportunities. In Curry, E., Scerri, S., and Tuikka, T., editors, Data Spaces, pages 337–357. Springer International Publishing, Cham.

Senthilvel, M., Oraskari, J., and Beetz, J. (2021). Implementing Information Container for linked Document Delivery (ICDD) as a micro-service. In Abualdenien, J., Borrmann, A., Ungureanu, L.-C., and Hartmann, T., editors, EG-ICE 2021 Workshop on Intelligent Computing in Engineering, pages 66–75.

van Nederveen, S., Beheshti, R., and Willems, P. H. (2010). Building information modelling in the Netherlands: a status report. Proceedings W078 - Special Track 18th CIB World Building Congress May 2010 Salford, United Kingdom, pages 28–40.

van Zandwijk, G. K. (2024). Seamless and Trustworthy Information Exchange in the Architecture, Engineering, Construction, and Operations Industry: the Governance and Development of a Data Space. Double Degree MSc Graduation Report, Eindhoven University of Technology.

Werbrouck, J., Pauwels, P., Beetz, J., Verborgh, R., and Mannens, E. (2023). ConSolid: A federated ecosystem for heterogeneous multi-stakeholder projects. Semantic Web, pages 1–32. DOI: 10.3233/SW-233396.

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