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Contributing to synchromodality through the implementation of a federated data space in Inland Waterway Transport

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ABSTRACT

Synchromodality aims to enhance freight transport efficiency by the synchronization of intermodal transport elements achieved through accurate, timely, and transparent information exchange, enabling real-time decision-making. Despite advancements in information technology and due to trust issues, data often remains siloed, which hinders synchromodality performance and operational targets. Federated data spaces offer a solution by creating decentralized ecosystems that facilitate the leveraging of critical data. This paper explores the potential of data spaces in the context of synchromodality. Through a case study in inland waterway transport, we demonstrate the practical application of a decentralized, open-source approach, illustrating how data space technologies can enable synchromodal transport. Our findings from the use case indicate that integrating data space technological actors beyond traditional transport stakeholders is essential for successfully implementing synchromodality. These actors can resolve interoperability and data quality issues, enforce data usage policies, and provide applications within the data space to execute needed tasks and services. We conclude that the effectiveness of data space deployment depends on well-defined, robust data usage policies, permitting data exchange among participants under agreed-upon conditions. Lastly, we recommend further research on governance mechanisms, value propositions, and business models for data spaces within the context of synchromodality.

1. Introduction

National forecasts from EU Member States anticipate a rise in industrial emissions in the coming years. Moreover, transport-related estimates indicate that emissions will be around 9 % higher in 2030 compared to 1990 levels unless additional measures are implemented [24]. Similarly, projections suggest a 180 % increase in freight transport demand in tonne-kilometers by 2050 compared to 2020 levels [48]. In fact, from 1990 to 2020, the domestic transport sector in Europe exhibited constant growth in greenhouse gas emissions, making it the only sector with such a trend [23], underscoring a widely acknowledged need for solutions.

Recognizing that different freight transport modes offer various service attributes, **multimodality** provides convenience by combining these modes. Multimodality requires freight to be transported using at least two different modes, with the modal shift decision influenced by factors such as cost, time, flexibility, reliability, and the nature and quantity of the cargo itself [55]. Moreover, building on the concept of multimodality, **intermodality** further enhances this integration by creating a seamless, single, door-to-door transport chain within one loading unit or vehicle [19]. In addition, intermodal transport represents a form of vertical collaboration characterized by Origin-Destination pair planning, which involves the advance booking of transport services covering the entire transit route before the cargo is shipped [38]. Although it requires greater coordination and managerial resources [15], intermodal transport offers benefits such as reducing traffic congestion and optimizing capacity utilization [2].

Despite potential benefits, implementing intermodal transport remains challenging. As highlighted by the EU Auditors' report, "EU still far from getting freight off the road" ([22], p. 2). For example, the percentage share of each mode in inland freight, expressed in tonne-kilometers for Europe from 2005 to 2020, reveals a clear trend

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toward increased utilization of road transport. Its share grew from 74.4 % to 77.4 %. On the other hand, inland water transport (IWT) and rail transport, considered greener alternatives, have generally declined during this period. Despite minor annual fluctuations, the share of rail transport decreased from 18.5 % to 16.8 %, and IWT fell from 7.1 % to 5.8 % [25]. These trends underscore significant challenges in the European transportation landscape, prompting the exploration of more innovative transport concepts.

An effective transportation system must optimally and sustainably use resources to enhance efficiency [54]. In this context, **synchromodality** expands upon intermodality by enhancing the dynamic nature of this transport concept by seeking modal shift based on real-time information. In other words, it exploits the combination of network planning and real-time mode switching [63]. Firstly, synchromodality underscores the importance of mode-free booking across different transport modes [36] and centers on "network-wide planning" [38], thereby providing higher flexibility in meeting transportation demands [7]. Secondly, synchromodality utilizes a comprehensive network based on information systems and a high degree of cooperation for the flexible adjustment of transport modes in real-time [61]. Furthermore, shippers who rely on a-modal booking and demonstrate flexible behavior for long-haul services can adopt cheaper, more sustainable transport solutions [32]. This is achieved by coordinating the various components of intermodal transport based on access to real-time information [16,45].

A 2023 report by the European Court of Auditors highlighted a major barrier to modal shift: the lack of easily accessible information on intermodal terminals and real-time network capacities [22]. In line with this, a key challenge in achieving synchromodality is the absence of real-time visibility [40] and “the need for a holistic platform that enables stakeholders to interact through technological services” ([31], p. 105), which is essential for coordinating diverse stakeholders and assets. Moreover, timely and accurate information can significantly enhance responsiveness to disruptions, reduce lead times, and improve service levels. However, in many transport and logistics contexts, the mechanisms needed to facilitate such information flow remain underdeveloped Zhang et al. [67]. This is particularly critical because how information is exchanged among stakeholders affects the modal split and market power balance between shippers and carriers [8]. From this perspective, a key challenge lies in developing a communication platform that is accessible to all stakeholders across multiple supply chains, enabling secure data exchange [56] and ensuring that trustworthy data from various parties is both accessible and usable.

The European Commission has identified data sovereignty as a central priority in shaping the digital economy of the future. Specifically, it has set ambitious targets to create data spaces that promote and facilitate trustworthy data-sharing practices and operations aligned with common societal values and existing legal frameworks [20]. In this context, Nagel and Lycklama [47] defines a data space as "a data ecosystem, defined by a sector or application, whereby *decentralized infrastructure* enables trustworthy data sharing with commonly agreed capabilities." In other words, a data space is a decentralized, soft infrastructure that allows multiple participants to discover and access data resources across different platforms while stakeholders’ data remains at its source rather than being centralized in a single repository, thereby preserving data sovereignty. This approach eliminates reliance on single software systems controlled by one entity and supports plug-and-play integration of the diverse systems and platforms participants use.

Different European data spaces have been initiated to promote the development of EU-wide, common, and interoperable data exchange in sectors such as mobility, agriculture, health, and industry/manufacturing [21]. Data spaces have the potential to enable synchromodality by improving the environment for data exchange and usage, particularly given the limited understanding of how to effectively motivate stakeholders to share valuable operational data, particularly in contexts requiring trust among stakeholders whose interests may not be fully aligned [67]. From this perspective, this paper explores the implementation of data spaces and their potential functionalities within the synchromodal transport context. Although the connection between data exchange and synchromodality is well recognized, the specific role of data spaces as enablers of such coordination remains under-researched. Accordingly, our study aims to explore strategies for enhancing synchromodality by addressing the following research questions:

RQ1: What is the connection between federated data spaces and synchromodality?
RQ2: How a data space can be implemented in the context of synchromodality?

While sharing information can be costly and relies on trusted relationships, new technologies offer solutions for continuous data flow while ensuring confidentiality and security for information owners in synchromodal ecosystems [12]. Our lessons learned from this implementation underscore that establishing trust mechanisms is fundamental to successfully implementing a data space under the concept of synchromodality. Moreover, building trust requires maintaining high-quality data standards, compliance with data exchange policies, and fostering stakeholder cooperation.

The synchromodal data space offers a flexible and scalable solution that integrates various technical components. By exploring the data space mechanisms and building blocks, this paper presents a generalized framework applicable to diverse scenarios within the transport domain. For instance, the *data interoperability* building block ensures consistent and efficient data exchange by proposing common standards, semantic models, and API utilization. These elements are mode-agnostic: whether the focus is on inland waterways, rail, road, or multimodal systems, the same interoperability principles can be applied based on the available stakeholders and resources. Meanwhile, *data sovereignty and trust* address the universal need for secure identification of participants, asset ownership, and appropriate data manipulation. By proposing the establishment of clear rules and trusted frameworks for sharing both sensitive and non-sensitive information, this building block is applicable in any transport context where data must be exchanged securely and with confidence.

Finally, the *data value creation* building block encourages the onboarding and active participation of diverse actors. It focuses on the discovery, provision, and realization of benefits from data products and services applicable across all transport domains. For example, by facilitating stakeholders to integrate new services and applications, the framework enables innovation in areas such as real-time (re)routing, modal capacity optimization, and predictive analytics.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on synchromodality and the concept of data spaces. Section 3 details the implementation of the data space, including a view of the data integrated and functionalities illustrated through a case study. Section 4 presents lessons learned from the implementation and provides an in-depth discussion linking the data space to synchromodality. Finally, Section 5 concludes the paper by highlighting its contributions and identifying potential directions for future research.

2. Literature review: exploring the connection of dataspaces and synchromodality

The literature on synchromodality is extensive, covering different perspectives. Early research focused on fostering cooperation among stakeholders [53] and integrating the latest logistics information into transport operations [46]. In the last decade, there was increasing recognition of the potential offered by real-time adaptation [52,54,60], along with the benefits of dynamic intermediate transfers in inland container transport [63,64].

In essence, synchromodal transport relies on the availability of real-time information in integrated systems that coordinate planning [61].

Equally important is timely access to this information, which is crucial for enabling adaptation to unexpected events or route improvements through real-time re-planning [35]. In other words, visibility within a synchromodal framework is determined by the accuracy, trustworthiness, and timeliness of the exchanged information, often facilitated by ICT/ITS platforms. However, it necessitates data infrastructures capable of managing (sensible) real-time data, among other technological challenges [6,31,43,62].

Similar to previous approaches, Ambra et al. [6] connect visibility and data transparency to reducing uncertainties in probabilistic models. Likewise, Yee et al. [65] developed a Markov decision support model incorporating real-time travel updates that, inspired by the Physical Internet concept, the authors argue that digital connectivity via digital platforms or control towers is essential for synchromodal planning. However, the paper does not delve into how data is exchanged among stakeholders in the network.

Several papers use various centralized sources of historical data in repositories to develop applications and optimization models and perform numerical experiments under the concept of synchromodality. Other papers propose digital platforms where stakeholders interact to find and pool synchromodal solutions. For example, Ferjani et al. [26] developed a decision support system based on a simulation-optimization platform designed to assess various potential itineraries and provide the optimal solution according to shipper preferences. In this approach, stakeholder data is centralized in the platform's database and stored in Excel files, which are then shared and processed internally between models within the platform.

Another example is the Synchro-Net platform presented in Giusti et al. [30] and Giusti et al. [33], which is built on Open Trip Planner (OTP), an open-source Java library originally developed for multimodal journey planning in urban contexts. The authors explain that OTP was extensively customized for freight logistics, enabling it to support synchromodality through multi-attribute optimization (e.g., cost, time, emissions) and advanced features such as risk analysis and multi-destination planning. The platform also employs extended General Transit Feed Specification (GTFS) formats to provide geospatial and scheduling data tailored for synchromodal transport, incorporates user-specific configurations, and includes tools like the GTFS Editor and Generator for data management. Additionally, it features a web-based visualization interface and supports APIs to ensure interoperability. This specific development is a clear example of the types of services that can be integrated into transport systems to enable synchromodality.

However, while these technical innovations demonstrate the potential for integrated synchromodal services, the platform's reliance on centralized infrastructure presents certain limitations. Synchro-Net's maritime cloud system stores data on centralized servers managed by third parties, with access and data sharing handled through login-based authentication. In this context, the authors acknowledge the drawbacks of such centralized setups and highlight the need for decentralized infrastructure to better address trust concerns when sharing sensitive information with external parties.

While these concepts demonstrate that real-time data sharing is fundamental and valuable for identifying optimal solutions in synchromodality, the overall data exchange process remains insufficiently defined, particularly concerning the conditions under which it occurs and the mechanisms that ensure trust and control over data usage. Furthermore, these platforms face the persistent challenge of data centralization, resulting in siloed information that is isolated from external stakeholders. This often confines data within proprietary platforms that require tailored IT developments and, in some cases, costly licenses, which hinder scalability.

Few papers have thoroughly explored data exchange, and fewer have related the concept of decentralized open and scalable systems to their research on synchromodality. For instance, Singh and van Sinderen [57] addresses the technical interoperability challenge between 4PL and LSP by integrating updated contextual information into their cargo shipments. This information includes data related to weather conditions, locations, traffic, water levels, and disasters, all presented in a consistent "common data format" such as XML files through EDI methods. Although the article addresses the inclusion of context data in synchromodal logistics, it does not delve deeper into the mechanism to effectively and trustfully exchange this information.

Hofman et al. [40] introduces some data space concepts to support coordinated governance and flexible data-sharing mechanisms in logistics and supply chain. The article suggests that semantic technology can enable synchromodality by facilitating data sharing and interoperability among various logistics stakeholders, including customers, service providers, infrastructure managers, and regulators. Similarly, Hofman [39] proposes a solution for creating a system-of-systems for data sharing in supply and logistics, with key elements drawn from the data space concept. While the authors' work introduces some concepts of data spaces and proposes federated systems to facilitate data sharing in synchromodality, it fails to demonstrate the practical development and implementation involving logistics companies and shippers.

In a nutshell, synchromodality necessitates continuous information exchange and spot interactions among stakeholders, contrasting with the discrete and limited information sharing in conventional hinterland transport networks due to trust issues [12]. From this perspective, developing an effective system for information exchange among diverse stakeholders, along with a clear understanding of the role of data exchange solutions in the development of synchromodality, remains essential.

Consequently, this paper does not aim to develop another optimization or rerouting model to test and apply synchromodality, as the concept has already been extensively explored in the literature, with clear results favoring synchromodal operations. Instead, we explore an approach to operationalizing synchromodality's reliance on real-time sensitive data exchange and leverage. In this approach, various stakeholders' data sources (sensitive and public) are dynamically offered, made available, and used by seamlessly integrating them into the data space. At the same time, participants could benefit from secure, decentralized, open-source solutions accessible to all stakeholders, regardless of their size, location, or market power, while maintaining interoperability, trust, data value, and governability, thus moving away from centralized, siloed platforms.

2.1. Overview of the data space concept

A Federated Data Space functions as a secure, decentralized, cross-organizational data network, enabling companies or other *Data Owners* to share data while maintaining its ownership and controlling its use by other companies or *Data Users*. In other words, the data space provides a decentralized soft infrastructure that adheres to established standards and shared governance models [50]. This environment facilitates the secure sharing and seamless integration of data within business ecosystems that collectively define regulations regarding security, compatibility, data protection, and contract structures [17,27]. Additionally, the ecosystem enables data exchange by connecting data owners, data users, and intermediaries from different organizations. It is supported by a *Data Space Service Provider* (DSP) or data space host, typically companies that provide software or digital services. The interaction of the various components and actors within a data space, such as the *Broker Service, Clearing House, App Store, Vocabulary Provider, Identity Provider*, and the users and owners of data, is illustrated in Fig. 1.

One of the core components in a data space is the connector. The *Data Space Connector* is a free, open-source tool designed for secure data exchange, ensuring that data providers maintain control over their data even after sharing. It allows for adding rules and conditions to the data and facilitates subsequent processing [42]. Additionally, it serves as an interface between the systems of data space participants, enabling data sharing under another crucial component for ensuring data sovereignty: *Data Usage Policies*. These policies establish the rules that safeguard data

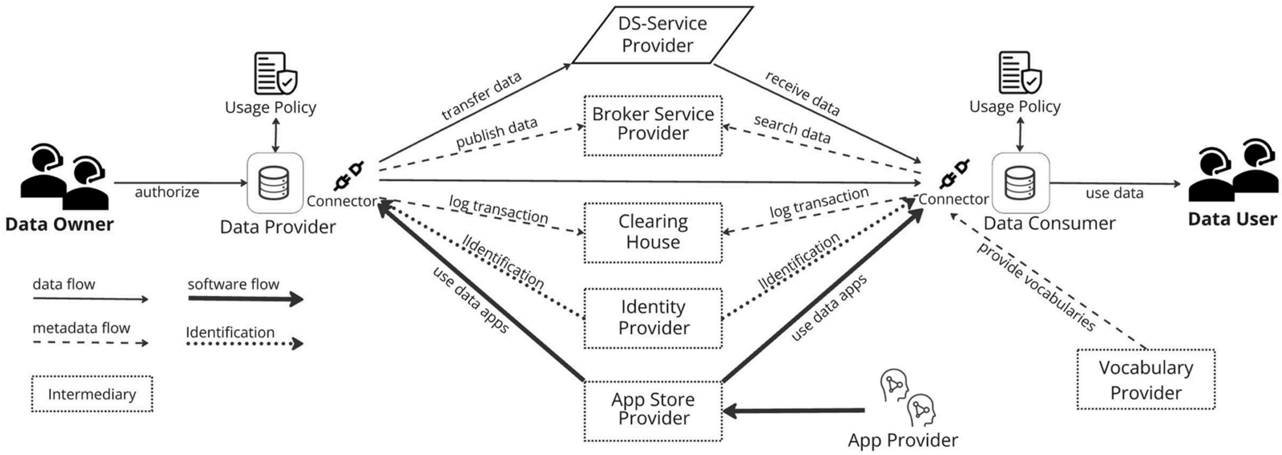


Fig. 1. Roles and interactions in a data space. Adapted from Otto et al. [49].
Metadata Broker: Provides information about data sources regarding content, structure quality, currency, and other features. **Clearing House:** Is the clearing and settlement service for all data exchange transactions within the data space. **Vocabulary Provider:** Provides standardized descriptors for data based on accepted best practices. **Identity Provider:** Provides services to create, maintain, manage, and validate identity information of and for data space participants. **App Provider:** Provides applications that can be deployed in the data space to execute different tasks and services (e.g., implementing optimizations/simulations).

and govern its exchange, outlining the obligations and duties that define the terms of use for the available data [41]. In addition, depending on the type of data and its level of restriction or confidentiality, these policies may either adhere to general principles or include more specific provisions. In short, the data space connector plays a crucial role as the standardized interface between different entities in the data space (Fig. 1), serving as the key element that connects core data space stakeholders (primary users) and intermediate participants offering various services. For a comprehensive description of the data space components, please refer to Pettenpohl et al. [51], and for control technologies to implement data usage policies on data sovereignty, refer to Fraunhofer IESE [28].

Finally, in the landscape of data space applications, by 2023, the International Data Space Association (IDSA) has deployed 113 applications across various industrial domains with different levels of implementation maturity [41]. Another example is Gaia-X, which, by 2023, has registered 91 applications, primarily in health (22), energy (17), and Industry 4.0/small-medium sized enterprises (14) [29]. The applications reported by IDSA [41] for the Supply Chain domain are described in Appendix A.1.

2.2. Overall reference for the data space development

To systematically approach the implementation of the Data Space, we propose a generalized reference framework based on foundational elements of the data space concept. Designed to be flexible and adaptable to synchromodal transport use cases, the framework serves as an overarching guide, with its implementation varying depending on the specific requirements and context of each case. It incorporates essential technical building blocks that align with the structure and needs of synchromodal transport, forming the foundation for secure, interoperable, and scalable data exchange across stakeholders and domains [47].

As suggested by Data Spaces Support Centre [13], the first building block, **data interoperability** (Fig. 2a), encompasses the standards and tools required for efficient data exchange, including semantic models, data formats, APIs, and mechanisms for provenance and traceability. For example, semantic data models should act as conceptual frameworks that define entities, relationships, and attributes while capturing the semantics or underlying meaning of data elements such as asset locations or the geographic scope of transport operations.

The second building block, **data sovereignty and trust** (Fig. 2b), refers to the identification of participants and assets, the establishment of trust, and the enforcement of access and usage control policies. The goal of this building block is to ensure the reliability and authenticity of participants and allow stakeholders to retain sovereignty over the data they choose to share. Achieving this requires the definition of clear data usage policies, the development of robust trust services, and the implementation of onboarding processes for stakeholders, particularly shippers, carriers, and logistics service providers, potentially leveraging existing agreements and ongoing commercial relationships.

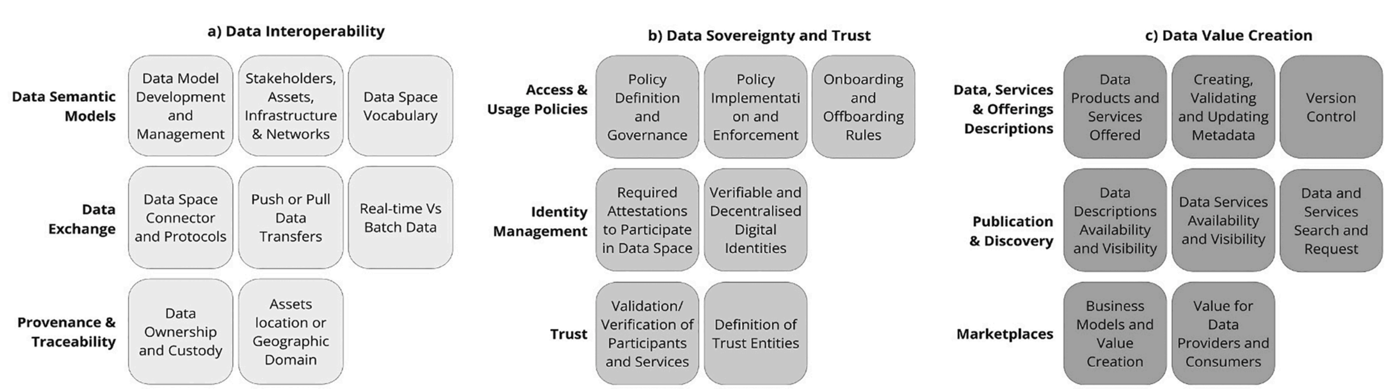


Fig. 2. (a) Data Space Building Blocks. Extracted from Data Spaces Support Centre [13]. (b) Data sovereignty and trust building blocks Extracted from Data Spaces Support Centre [13]. (c) Data value creation building blocks Extracted from Data Spaces Support Centre [13].

Finally, the third building block, **data value creation** (Fig. 2c), includes capabilities that support value generation within a data space, such as the registration and discovery of data offerings or services, as well as the provision of value-added functionalities. In the context of synchromodality, value creation is achieved through the seamless integration of both internal and external services and applications into the data space. This enables dynamic modal shift decisions by leveraging real-time data through various application services and enhances operational insights by enriching existing datasets with additional sources, such as combining vehicle positional data with cargo information and infrastructure availability. For a comprehensive overview of the building blocks' detailed components and interactions in the data space, see Data Spaces Support Centre [14].

3. Implementing the data space for synchromodality: A Inland Waterway Transport use case

As presented in the previous section, the proposed framework offers a general yet adaptable structure for enabling data exchange and service integration through data spaces. It is designed to be flexible, allowing its building blocks to be developed to the specific needs of different case studies, transport modes, and stakeholder configurations. This section presents a concrete use case within the context of inland waterway transport.

3.1. Data space set up in practice

To facilitate synchromodal solutions and promote the development and implementation of data space technologies among European industrial and logistics players, we aim to establish a data space in the Flemish region of Belgium, originating from the Ghent area. The companies involved have extensive experience in the European logistics network, are well-versed in regional challenges, and understand the diverse range of stakeholders and infrastructure.

In terms of modal share, trucks are the primary mode of transport for most companies, as expected, with inland barges being the second most utilized mode (see the companies' profile in Appendix A.2). In addition, some shippers have encountered challenges due to limited visibility in IWT transport execution, where key areas for improvement include refining laycan definitions, which refer to the agreed-upon period during which a chartered vessel must arrive for loading [3], enhancing in-transit visibility for decision-making, and improving time of arrival estimations for primary inland waterways and terminals. These uncertainties often result in underutilizing IWT routes, thereby limiting synchromodal alternatives. By focusing on inland waterways freight transport as the use case, we aim to explore the potential of data space development in addressing these challenges. Finally, Fig. 3 displays the two main inland waterways routes covered: the Rhine-Alpine (RALP) to Basel and the Rhine-Main-Danube to Bratislava, both departing from the Ghent area.

This section explores a practical approach to the data space. First, it is important to note that within the Synchromodal Data Space, each stakeholder's role is shaped by their characteristics and business interests. While stakeholders can be treated as independent participants with multiple roles within a data space, for our demonstrator, we group *data owners* and *data providers* as a single stakeholder, as well as *data consumers* and *data users*. Additionally, stakeholders may act as both a data provider and a consumer.

The transport process aligned with the data space is illustrated in Fig. 4 and follows a straightforward sequence. Initially, a vessel has not yet been nominated for a specific task by the barge operator. Its location and relevant data are accessible only to users compliant with the data asset's *nomination policy,* a data usage policy that permits stakeholders to track vessels when a barge is nominated or proposed for nomination for a specified period. Additionally, access may be regulated by a *geographical policy*, which is not restricted to active nominations but is based on geographical boundaries.

The data can be accessed if it describes data relevant to a certain area. In our case, this refers to data pertinent to particular waterway authorities (e.g., Wasserstraßen und Schifffahrtsamt (Germany)), which holds legitimacy over certain data captured and generated within a designated zone (e.g., RALP waterways). Consequently, the data-sharing process begins when relevant stakeholders within geographical areas of interest are involved or when the barge operator (or LSP) nominates a specific barge for a task. This nomination links the vessel (identified by its name and MMSI) to a transport assignment detailing the loading terminal, the scheduled arrival time window for loading (laycan), the intended destination, and the agreed arrival date. As soon as the nomination is formalized, the next phase is triggered, and data consumers included under the nomination policy start receiving the relevant information. Notably, these nominations can also be executed in bulk for an entire fleet of barges.

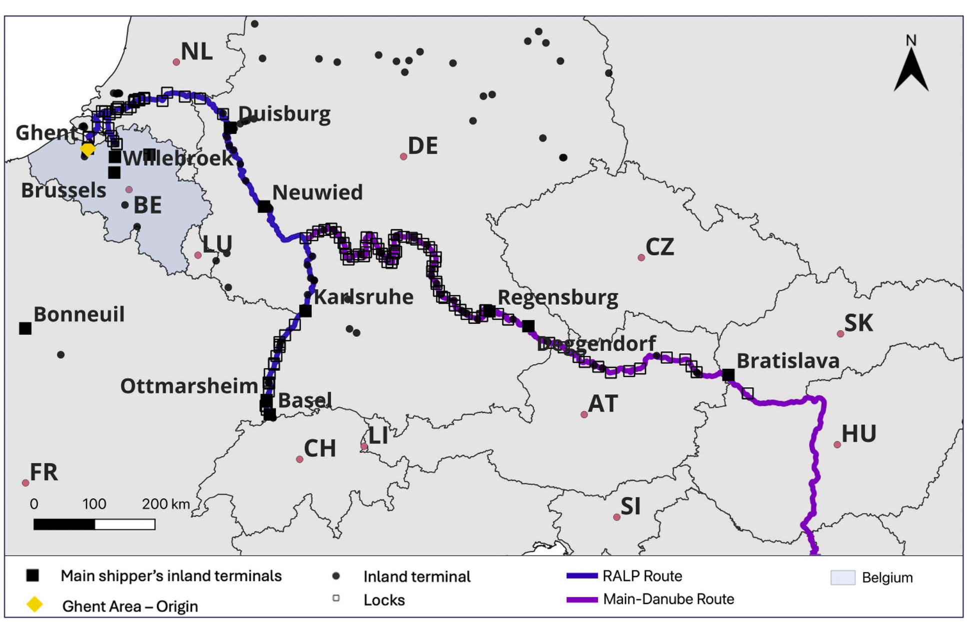


Fig. 3. Inland waterways and facilities covered in the data space.

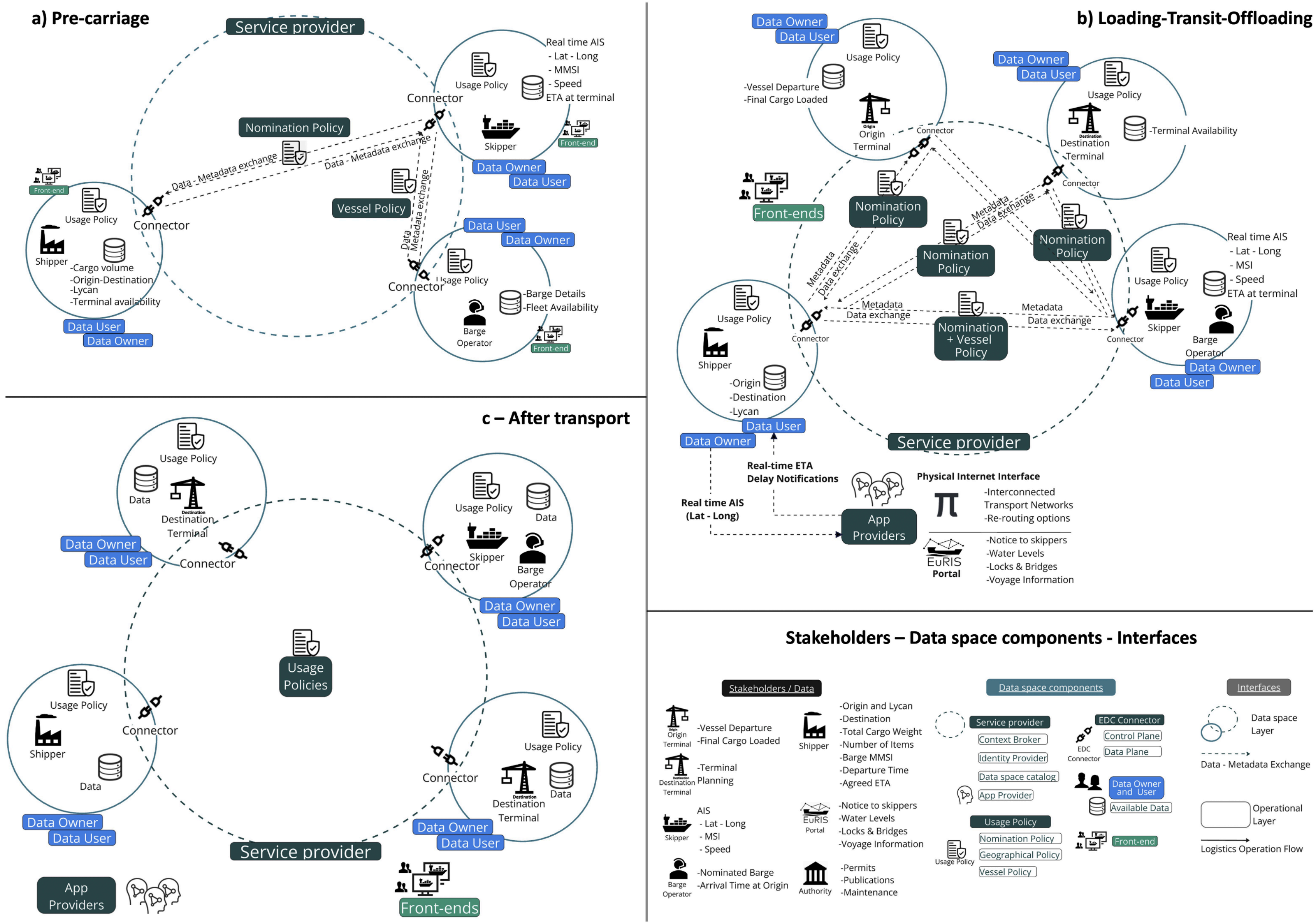


Fig. 4. Synchromodal data space implementation overview during transport stages. (Actors and data shared within stages are not exclusive).

Pre-Carriage: Once the nomination is complete, the nomination policy takes effect, and the barge moves into the pre-carriage phase (Fig. 4a), regardless of whether it is already en route to the loading terminal. At this point, the shipper, responsible for cargo preparation, gains lawful and proportionate access to the relevant data, enabling the shipper to use the agreed-upon information for internal planning. These preparatory tasks, which are highly sensitive to any early or late barge arrival, include organizing the cargo and loading areas for operations, clearing the loading berth (e.g., arranging pilots for deep-sea vessels), notifying the port operator, inspecting loading equipment, and coordinating cargo surveyors and stevedores.

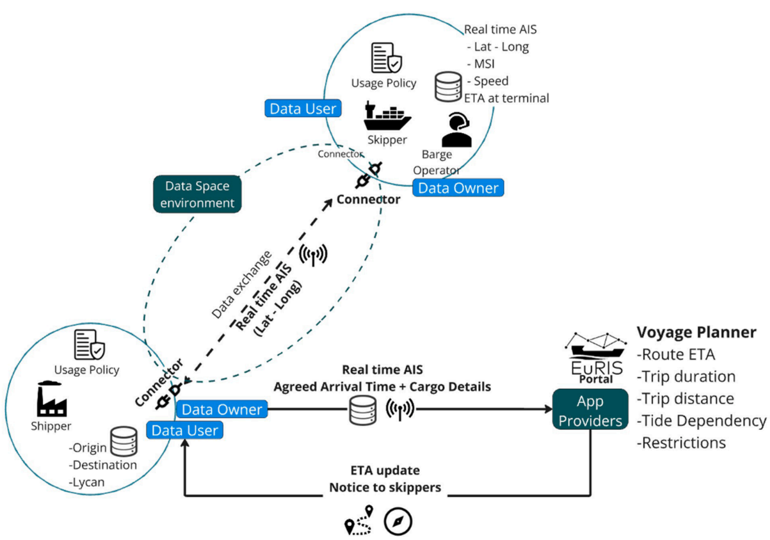
Loading – Transit – Offloading: Upon the vessel's arrival at the loading terminal, cargo identification, details, destinations, and ETA are made available. The planned information is then updated with the actual loading time and the quantities of cargo placed on the barge. Once loading is complete, the vessel departs for the destination terminal, marking the beginning of the transit phase (Fig. 4b).

During this phase, we use the inland Automatic Identification System (AIS) position and the destination terminal to calculate the Estimated Time of Arrival (ETA) in real-time, which is then compared against the agreed arrival date. Real-time voyage calculations are performed using the voyage planner endpoints available through the EuRIS portal. EuRIS is a platform that supports traffic and transport management in inland navigation. It integrates River Information System (RIS) services by aggregating data from inland waterway management organizations across 13 European countries and, where technically feasible, provides interfaces with other transport modes [10]. For further reference, see https://www.eurisportal.eu/ (Accessed 2024–07–05).

An active triggering algorithm is used as a service within the data space (See app provider in Fig. 1) to continuously monitor the feasibility of the assignment and the likelihood of a timely arrival. Moreover, within the data space, the ETA calculation is triggered by events occurring during the transport stage and is based on the barge's real-time location. In the case study, when a potential delay is detected, the system issues alerts to inform stakeholders, enabling them to take countermeasures or corrective actions. This functionality also opens up opportunities to leverage rerouting application services. For a detailed documentation of the voyage planner, see the EuRIS Routing Web Service (last accessed: 2024–05–05). The following example (Fig. 5) illustrates an ETA calculation using the EuRIS voyage planner:

Finally, similar operations can be performed using various technological developments integrated as data space services, in a similar way voyage planning and ETA updates are currently executed using EuRIS. For instance, the products/services described in Giusti et al. [30] and Giusti et al. [33] illustrate this potential. The GTFS Data Generator Batch is designed to automatically create GTFS-compliant routes using data from OpenStreetMap and commercial sources. Another example is the Multi-Attribute Optimization Engine, which identifies optimal synchromodal routes by combining truck, train, and ship options while minimizing multiple (often conflicting) factors such as cost, time, and emissions. Additionally, the Risk Analysis Module, developed by Fraunhofer, exemplifies a data space service that applies Monte Carlo simulations to provide Key Risk Indicators of selected itineraries, evaluating aspects such as safety robustness, flexibility, and potential deviations in cost or time.

After transport: The data-sharing process and transport assignment



Voyage planner: Ghent - Basel

```
Calculating route
from BEGNE053240000000137
to FRXXXVN4070000001683...
Duration: 13547 minutes
Total length: 866715.7330973425m
Tide Dependent: False
Lowest CEMT class: O
Permissible dimensions:
Depth: 160cm
 Length: 1300cm
Height: 200cm
Width: 450cm
Departure from
Kanaal Gent-Terneuzen km 13,7
```

Voyage planner: Ghent - Regensburg

```
Calculating route
from BEGNE053240000000137
to DEREG00401HRBA123732...
Duration: 5818 minutes
Total length: 1186588.4612651535m
Tide Dependent: True
Lowest CEMT class: O
Permissible dimensions:
  Depth: 250cm
  Length: 5000cm
  Height: 400cm
  Width: 505cm
Departure from
Kanaal Gent-Terneuzen km 13,7
```

Fig. 5. Continuous voyage computation using EuRIS Portal.

conclude with the vessel's arrival at the destination terminal, where the task is finalized with the notification of offloading. At this point, similar to other usage policies, the vessel becomes untraceable to the involved data consumers (or falls under the applicable usage policy restrictions) as per the nomination policy (Fig. 4c), marking the end of the data-sharing cycle for this specific logistics assignment.

3.2. Overview of the implementation

Since, for our data space development, inland AIS data alone is insufficient without transport details, a key element is making the planned IWT trip durations and cargo details (see Table 2) available to relevant stakeholders in the data space. This provides critical insight into future trip execution and operational needs. For example, Fig. 6 presents box plots comparing the shipper's estimated trip durations made in advance during the pre-carriage stage with 45 actual trip durations (based on the barges' inland AIS data) during the transit stage for the main routes departing from Ghent area.

Valuable insights can be drawn from the differences between planned and actual trip durations. For example, there are variations for most destinations, with the only destination where the actual arrival occurs earlier than the estimate being DEDUI (Duisburg). In contrast, the actual and estimated values are relatively close for CHBSL (Basel). In addition, more significant discrepancies are observed for destinations such as FROTM (Ottmarsheim) and those along the Rhine-Main-Danube Canal, where actual trip durations exceed the planned estimates. Furthermore, destinations like SKBTS (Bratislava) have a fixed planned trip duration of 14.5 days, while others, such as DENEU (Neuwied), show more variability. This information is a starting point for identifying triggers and deviations in trip executions.

Another significant aspect of the data space implementation is the potential for event-based real-time data sharing, where data usage policies in the use case are triggered at key moments. For example, Fig. 7 shows the data space front end from the shipper's view, where an appointed barge (identified by its MMSI and name) in pre-carriage status is en route to the loading terminal in Zelzate (Belgium) with a Planned Time of Arrival (PTA). In this instance, the Planned Time of Arrival (PTA) is scheduled for Friday, December 8, 2023, at midnight, nine days from the required arrival time at that moment. However, the ETA, based on the barge's real-time position, is less than one hour away.

The previous example demonstrates clear opportunities for optimization. A barge could either continue waiting for days in its current position until the agreed-upon loading date, or this information could be leveraged by the shipper and transporter to potentially synchronize operations. If the shipper and terminal are flexible, loading could be moved forward, allowing for more efficient use of resources and freeing up the barge and the terminal for other activities sooner. This information is critical for improving synchronization and ensuring the barge and terminal are aligned with the most efficient schedule possible.

A final comment pertains to interoperability and the need for equivalency between the stakeholders' nomenclature and the EuRIS nomenclature (or other relevant systems) to reference different locations and incorporate them into the data space. To ensure compatibility with the EuRIS portal, Table 1 provides examples of matched UN/LOCODEs for various locations alongside their corresponding RIS Index.

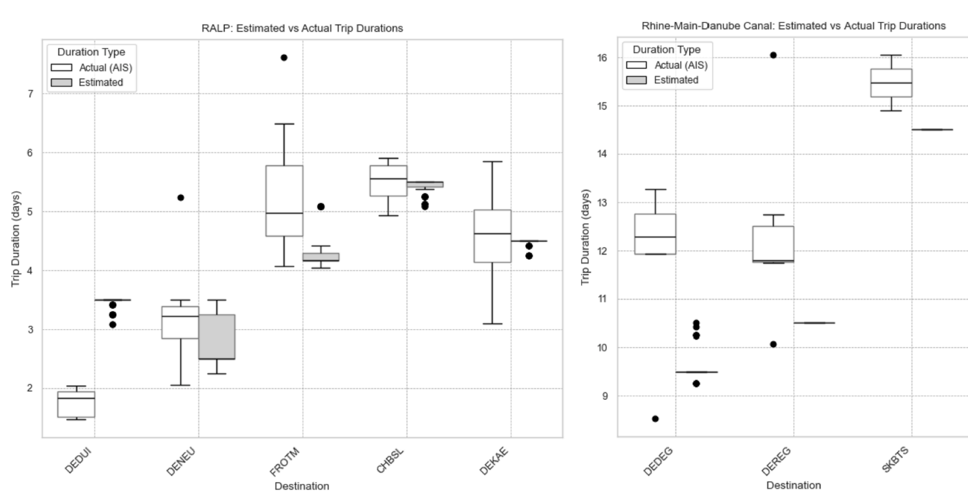
The EuRIS nomenclature facilitates the translation of stakeholder terminal names and locations from internal Transport Management Systems into a common language within the data space. This integration enhances the understanding of inland waterway transport and supports strategic planning and execution of logistics operations, underscoring the importance of this data in improving the competitiveness of inland waterway transportation within synchromodal applications. Additionally, the connection with the EuRIS voyage planner enables dynamic monitoring of trip performances.

3.3. Description of the data integrated into the data space

The primary data sources integrated into the data space include AIS from barges serving the shippers, inland transport-related data associated with specific transport assignments during both the planning and execution phases and information regarding inland waterways status. Table 2 summarizes the data and its sources integrated into the data space.

The connection between AIS data and the data space is twofold. First, AIS data from inland barges requires confidentiality, as barges often serve as homes for skippers and their families [59]. Second, it involves a certain level of complexity (big data), making it suitable for effectively testing the principles of the data space. In this respect, while publicly available commercial sources exist for AIS data, official access within the IWT ecosystem in Europe requires stakeholders to comply with the General Data Protection Regulation (GDPR).

In terms of GDPR, our approach aligns with the services provided by EuRIS [18] (see: https://www.eurisportal.eu/trafficimage, accessed: 2024–05–05). For example, in our case, the AIS data flow relies on the shipper's consent and access permissions granted by the barge skipper or fleet operator, enabling the tracking of the position and identification of barges involved in specific transport assignments arranged by the shipper. On the other hand, in our case study, inland AIS data alone is



(a) Rhine-Alpine (b) Rhine-Main-Danube Canal

Fig. 6. Boxplot of distribution of barges trip per destinations from Ghent Area.

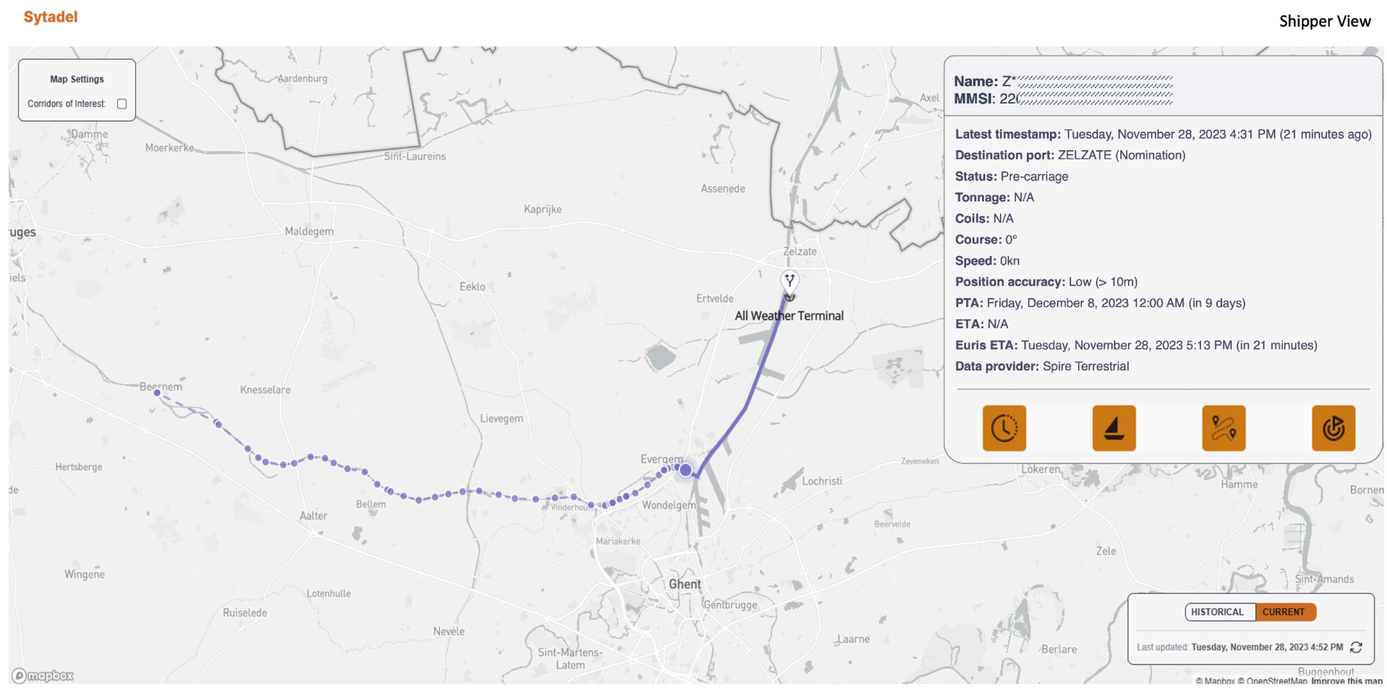


Fig. 7. Synchromodal data space front end "Shipper's View".

Table 1
Mapping between UN/LOCODE and RIS Index.

UN/LOCODE	RIS Index
BEGNE	BEGNE053240000000137
BEANR	BEANR02H01L039300000
DEDUI	DEDUI03901HRBS107805
FRBNL	FRXXXVG221BER0101738
DENIW	DEXXX039010000006068
SKBTS	SKBAB00001BER1718663
DEKAE	DEKAE03901HRBA103599
FROTM	FRRDVVN188TRM0101958
*CHBSL	FRXXXVN4070000001683
DERRG	DEREG00401HRBA123732
DEDGG	DEDEG00401TRM0122831
ROGIU	ROGRG00001BER1104922

Note: *CHBSL refers to Basel, Switzerland, which is not part of the EuRIS portal. Therefore, some of the nomenclature relates to its nearest EuRIS member location, in this case, the France-Switzerland border along the Rhine.

insufficient without the availability of inland water transport details, making it necessary to incorporate complementary information.

First, we included the shipper's planning information, which contains specific transport needs, such as the tonnages (or list of items) to be delivered per week, the nominated barges names and identifications, cargo details, unique delivery identifiers, and the agreed arrival date between the shipper and carrier.

Moreover, the agreed arrival time is crucial, as it indicates when the barge is expected to arrive at its destination, distinct from the time it takes to reach it. Second, we incorporated the shipper's outbound information, including the actual departure of the barge from the terminal, the barges' names and IDs performing the tasks, and the final cargo details on board, including destinations. This information is essential for determining the actual time of departure (ATD) of the barge from the origin using the AIS data and geofencing and for establishing an ETA that considers the status of the inland waterways.

Finally, data such as disruptions can create value and visibility for stakeholders (e.g., Singh and van Sinderen [57]). In this context, we have included Notice to Skippers (NTS) across the inland waterways and water levels at critical locations integrating the EuRIS platform API (see: https://developer.eurisportal.eu/docs/nts/, accessed: 2024- 05–05). NTS data provides details on events occurring in inland waterways during a notice period, including start and end times, types of limitations, descriptions, geographical positions (latitude and longitude), and identification codes of the affected objects. In addition, these NTSs are released in near real-time after an event is reported and adhere to the schema established by the European Union for standardized information exchange in the inland navigation sector.

For example, Fig. 8 displays all NTS messages from 2023, highlighting those that indicate navigational limitations in the RALP corridor between Belgium and Switzerland. The map illustrates the concentration of events (depicted as black dots) along a section of the RALP, while the heatmap shows the frequency of the top five most severe events affecting various inland waterway infrastructures, based on the CESNI [11] classification. Notably, the *OBSTRU* event, representing a blockage, has a particularly high frequency at locks (i.e., *LCK* and *LKB*) and Fairways (i.e., *FWY*), while *NOSERV* (no service) frequently occurs at harbors (i.e., *HAR*).

In this respect, this information, combined with lead times, terminal availability, barge planning, and barge positions, is crucial when deciding, for instance, whether to accelerate a barge's arrival at the loading terminal to avoid potential or actual disruptions along the fairway that could cause transit delays. This is especially important given the many locks a barge must pass through, particularly the Rhine-Main-Danube Canal, as shown in the map in Fig. 3.

4. Discussion

In the previous section, we presented the implementation of synchromodal data space functionalities. This implementation offers a viable alternative to enhance the timely and trustworthy exchange of valuable data among diverse stakeholders involved in synchromodal operations while adhering to predefined data usage policies. Additionally, it contributes to the literature (see, e.g., Hofman [39]; Giusti et al. [31]; Singh et al. [58]) by supporting the real-time nature of synchromodal transport through a decentralized approach using open-source standards (i.e., Data Space connector), as emphasized by Almotairi

Table 2
Data descriptions and sources.

Data	Description	Source	Type
Ship identity	Name of the vessel	AIS Barge	String
MMSI	AIS ship identity		Integer
Ship size	Size of the ship		Float
Ship position	Latitude and Longitude (WGS84)		Float
Ship Speed	Current speed of the ship		Float
Ship Course	Current navigation direction		String
Timestamp	Time of position report		DateTime
ETA	Estimated Time of Arrival	Barge Skipper	DateTime
MMSI	AIS ship identity of appointed vessel	Shipper Plan	Integer
Ship identity	Name of the appointed vessel		String
VO	Unique cargo delivery number		String
Terminal origin	Planned loading terminal		String
Terminal destination	Planned destination of the cargo		String
Loading date	Planned loading date at origin		DateTime
Agreed arrival date	Date of agreed time of arrival		DateTime
MMSI	MMSI of actual ship with cargo	Shipper Actual	Integer
Ship identity	Identity of final loaded barge		String
VO	Unique cargo delivery number		String
Terminal origin	Actual loading terminal		String
Terminal destination	Actual destination of the cargo		String
No. of items	Final No. of loaded items		Integer
Item weight	Final cargo total weight		Float
Loading date	Actual loading date at origin		DateTime
Vessel departure	Log when vessel departs origin terminal		DateTime
Terminal RIS	RIS Index of a terminal	EuRIS	String
Terminal position	Latitude and Longitude for terminal		Float
Voyage plan	Estimated from EuRIS		String
Trip Distance	Estimated from EuRIS		Float
NTS	Events occurring in waterway		String
Water level	Water levels at critical locations		Float
ETA	ETA from EuRIS portal		DateTime
UN/LOCODE	UN location code of a terminal	Database	String
City	City corresponding to a terminal		String
Country	Country corresponding to a terminal		String
Terminal polygons	Terminal geofencing polygons		Polygon

RIS: River information system - **EuRIS Portal:** Public information shared by 13 waterway authorities. (see: https://www.eurisportal.eu, accessed: 2024–07–05).

et al. [4] some years ago.

4.1. Lessons learned from the implementation

In the early stages of implementing the synchromodal data space, existing baseline contracts and commercial relationships are crucial. These are expected to evolve as trust in data usage policies, along with smart contracts and blockchain technologies, expand. Such contractual agreements between shippers, LSPs, barge operators, terminals, and other stakeholders are key in aligning interests during the initial deployment stages of the data space. Moreover, in response to increased trust needs, some usage policies and overarching agreements have been revised to fulfill data criticality demands. While not all participants initially used the data space connector directly, establishing robust and clear standard data usage policies, compliant with fundamental regulations such as the GDPR was advantageous. For example, these policies encouraged initial trust among data owners and users, reinforced through diligent monitoring of policy implementation. In other words, trust is critical in this context; without it, maintaining high-quality standards of the data space is a significant challenge.

Based on existing data usage policies (e.g., permissions, prohibitions, and obligations), additional use-for-purpose policies with different obligations can be employed upon identifying a valid new route, mode, or alternative. In this respect, control policy patterns proposed in Dataspace Connector [14], such as "Connector-restricted Data Usage," permit data usage for a specific connector, meaning specific data is only shared with particular stakeholders. Similarly, a "Use Data and Delete it After" policy can allow data usage within a specified time interval with the restriction to delete it at a specified timestamp. Consequently, data will be retained only as long as necessary for the intended purposes and will be securely deleted afterward.

Secondly, the issue of data quality is essential. Inconsistencies in AIS coverage areas exemplify this concern, with certain European waterways lacking full coverage, often due to geographical challenges like mountainous terrain or lack of terrestrial receivers, thus resulting in gaps in historical route data for vessels or real-time signals. Furthermore, the availability and uptime of cargo data are critical. It is essential for AIS sources to offer real-time visibility of the entire fleet and for relevant stakeholders to provide cargo details and terminal and logistical planning information to ensure timely access to the most current, relevant data regarding cargo and planning. Although AIS and transport mode location gaps can be complemented with other satellite sources, it is essential to study and identify the main hinterland areas with signal gaps and proactively anticipate lost signals.

A third note is related to interoperability. While data sharing for AIS data (or similar position tracking systems for other transport modes) is standardized and widely recognized, the sharing of information regarding vessel nominations, logistics planning, terminal schedules, and other pertinent details often presents greater challenges. This is evident even within the scope of this implementation. For instance, inconsistencies arise due to varying naming conventions for specific locations and different cargo descriptions. Additionally, from an integration standpoint, it has become clear that the existing IT infrastructure supporting logistics operations is not optimally configured for interoperable data exchange. For instance, this infrastructure frequently depends on ad-hoc exports in flat files or similar methods to disseminate data among various stakeholders. From this perspective, services in the data space to overcome such challenges could include strong metadata management to ensure data is updated in real-time and accessible to all relevant parties and services free of inconsistencies. Our initiative is only an example that explores the potential of various available data sources that can be integrated to develop diverse applications and services within the data space.

4.2. Linking data space functionalities with synchromodality

The data space has the potential to fulfill several visibility characteristics identified by Caridi et al. [9], which are crucial for successful synchromodal operations. These characteristics include: (i) ensuring access to critical information both within and outside the organization, vital for overseeing and adjusting operations; (ii) allowing stakeholders to access or exchange relevant information, benefiting all parties involved; (iii) enabling stakeholders to receive notifications about deviations in supply chain operations and respond accordingly; and (iv) providing visibility as a tool for gathering and analyzing supply chain data, supporting decision-making and reducing transport-related risks. Additionally, the data space approach also advances the literature on mechanisms that enable technologies to support synchromodality [31]. These mechanisms include *traceability* of transport modes and routes using geolocation (e.g., AIS data and terminal geofencing), *optimization/rerouting* capabilities that incorporate data from owners via app providers, and an integration platform where entities, such as

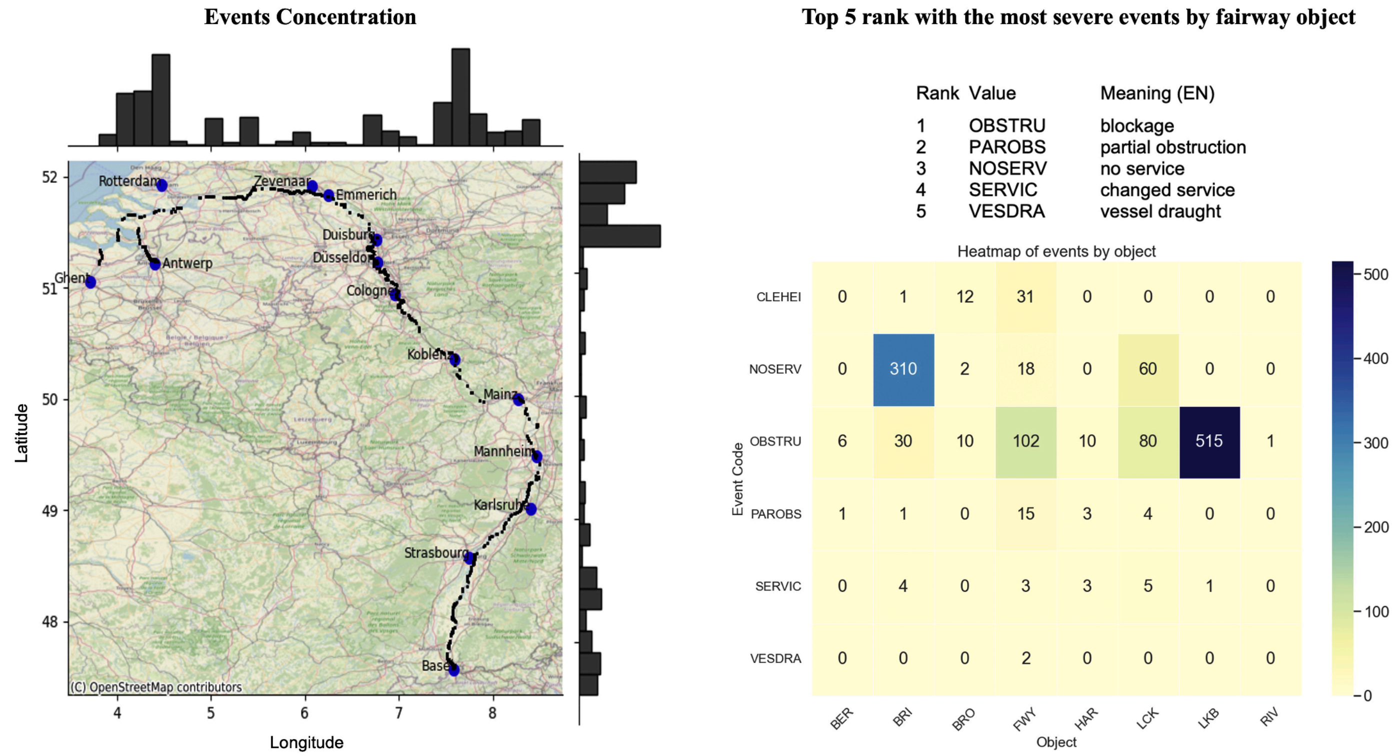


Fig. 8. Events concentration and heatmap for 2023 from NTS.
Heatmap objects abbreviations: BER: Berth - **BRI**: Bridge - **BRO**: Bridge Opening - **FWY**: Fairway, **HAR**: Harbour area or basin - **LCK**: Lock - **LKB**: Lock basin (*related to a lock) and **RIV**: marks along the waterway.

orchestrators [12], can mediate synchromodal operations while maintaining information exchange balance.

The impact of the synchromodal data space extends beyond visibility, contributing to other key characteristics of synchromodality. One notable contribution is the integration of multiple stakeholders in a decentralized, collaborative effort that spans various sectors or industries. This integration requires coordinating and managing a system composed of interconnected supply chains or networks [35,43,61], rather than focusing solely on the isolated platforms and supply chains of individual stakeholders. This approach promotes community-building within supply chains by enabling decentralized data connections among trusted stakeholders. The collective commitment of stakeholders to integrate the data space connector, make their data discoverable, and utilize it according to agreed-upon usage policies represents an integration that goes beyond traditional transport contracts, potentially evolving into dynamic partnerships. However, the extent to which this transformation will occur in larger setups remains uncertain and is worth further exploration.

Current data space applications in various domains, as reported by the IDSA [41] and Gaia-X [29] initiatives, exemplify how a wide range of organizations and stakeholders, each with different core businesses and objectives, can be successfully integrated. Similarly, this is relevant in the context of synchromodality, which extends beyond traditional transport and logistics actors such as shippers, carriers, LSPs, authorities, and terminal operators. It also involves the inclusion of entities that may be considered external to core logistics operations, such as *data space service providers*, *metadata brokers*, and *app providers* (see Fig. 1). In other words, these additional actors reflect the increasing potential for recent research in synchromodal logistics to be delivered as modular services within the synchromodal data space.

Adapting to shifting demands and disruptions in synchromodal transport relies on the availability of flexible services that align with real-time demand and shipper preferences, thereby minimizing idle capacity and improving vehicle utilization [67]. To illustrate how recent research can support the development of such services within a synchromodal data space, Table 3 presents some potential services derived from academic contributions. These services address key operational challenges, including routing optimization, capacity management, real-time orchestration, and strategic planning under uncertainty, and demonstrate how the integration of research-based solutions can enhance the overall functionality of the data space.

4.3. Data space applicability: beyond inland waterway Transport

The use case presented in this paper primarily focuses on the inland waterway transport ecosystem, addressing the specific stakeholders and their needs for data products and services derived from deploying a data space. However, it is important to highlight that the proposed framework is not limited to IWT; it can be further developed and adapted to suit or integrate various transport domains depending on the stakeholders, the objectives of the data space, and the available assets and resources.

Interoperability refers to the capacity of different systems to operate together seamlessly, enabling devices, applications, or products to connect and exchange information in a coordinated manner without requiring additional effort from end users [13]. In the context of road transport, positional data from vehicles follows a structure similar to that of AIS used in IWT, which enables comparable integration into the data space architecture.

As described by Adam et al. [1], in 2016, Belgium introduced a kilometer-based taxation system for heavy-duty trucks over 3.5 t, equipping each vehicle with a Global Navigation Satellite System (GNSS) device that records its location every 30 s. While originally intended for tax billing, this positional data can also be repurposed to address broader operational challenges in transport systems. In this respect, a truck fleet operator can define a geographical data usage policy triggered by potential delays (e.g., a late-arriving barge), allowing truck positions and ID to be shared with relevant stakeholders in the

Table 3
Research-based services for synchromodal data spaces.

Source	Service	Description
Practice-based from the use case	Transshipment Infeasibility Prediction	Monitors the operational status of transshipment points and predicts potential infeasibility caused by delays. Leverages real-time data to trigger shipment rerouting decisions.
Zhang et al. [66]	Dynamic Routing and Scheduling Optimization	A service using heuristic algorithms to flexibly optimize transport routes and resource allocation in real-time, reducing operational costs while adapting to transport disruptions.
Guo et al. [37]	AI-Based Shipment Matching	A decision-support service using a Reinforcement Learning Algorithm (RLA) to optimize shipment-to-service matching under dynamic and stochastic travel times considering travel time uncertainty. The RLA pre-learns value functions through simulation, allowing immediate adaptation of shipment routing decisions when real-time travel data is revealed.
Yee et al. [65]	Real-time Adaptive Orchestration	Integrates real-time data feeds (e.g., traffic, infrastructure usage, disruptions) to dynamically adjust transport schedules and mode choices for improved system-wide responsiveness.
Giusti et al. [34]	Facility Location Optimization	Optimizing the location of transshipment facilities and allocating freight flows under uncertainty and allocating freight flows across facilities while ensuring operational synchronization.
General	Uncertainty-based Scenario Analysis	Generates and evaluates multiple planning scenarios to assess the impact of uncertainties in capacity, infrastructure, and handling performance. Utilizes data such as historical disruptions, weather, and demand shifts to support resilient and informed logistics decisions.

data space. This enables real-time coordination with terminals and carriers, facilitating operational decisions like truck rerouting, reallocation of cargo handling activities, and partial transshipments when urgent cargo must be prioritized. Additionally, reference data such as terminal locations and nomenclature can be standardized using the EuRIS nomenclature introduced in this paper.

A clear example of how truck and barge operators can benefit from a data space is the Real-Time Schedule Co-Planning approach proposed by Larsen et al. [44]. In this model, barge operators propose departure schedules based on historical performance data and uncertainty metrics. Truck operators then assess these proposals by simulating associated costs and providing aggregated feedback, which enables mutual schedule adjustments. This approach aligns well with the data space vision, as it supports secure, efficient, and collaborative optimization between barge and truck operators while preserving data sovereignty. Table 4 outlines the data characteristics of this integration, which, when combined with other datasets (e.g., Table 2), can significantly enhance multimodal synchronization.

Finally, we can learn from Table 4 how standardized and real-time data integration between transport modes can support coordinated decision-making and enable data-driven services. These insights underscore the potential to develop data spaces tailored to various transport modes and operational contexts, not limited to inland waterway transport, but applicable across the broader multimodal logistics landscape.

Table 4
Key Data for truck-barge integration.

Data	Description	Source	Type
GNSS Data for Trucks			
ID	Unique truck identifier	Onboard GNSS	Integer
Truck Position	Latitude and Longitude (WGS84)		Float
Timestamp	Date/time of position report		DateTime
Velocity	Current ground speed of the truck		Float
Direction	Heading of the truck		String
Country Code	Country code of truck registry		String
Euro Value	Emission standard class (e.g., Euro 5)		String
MTM	Maximum permissible mass data		Float
Real-time co-planning Data			
Barge Location	Current terminal where the barge is docked	AIS systems	Binary
Barge Schedule	Planned departure times from terminals	Fleet operator	DateTime
Container Demand	Volume of containers needing transport (by destination)	Booking systems	Float
Truck Availability	Number of available trucks at terminals or sur-roundings	GNSS/Fleet operator	Float
Cargo Inventory	Containers waiting at terminals	Terminal systems	Float
Travel Times	Road and waterway transit durations between nodes	AIS/GNSS	Integer
Barge Capacity	Maximum number of containers per barge trip	Barge operator	Integer
Operational Costs	Costs for delays, routes, and barge/truck de-partures	Private Contracts	Float

5. Conclusion

Our research proposes a decentralized approach to managing data relationships and interfaces among diverse stakeholders, representing a departure from traditional centralized models and applications. Additionally, by employing open-source connectors, the data space approach offers a scalable solution adaptable for entities of various sizes and sectors, addressing the prevalent issue of trust in data exchange and democratizing access and participation in synchromodal transport solutions. Moreover, exploring neutral data governance mechanisms and data value propositions or business models for the synchromodal data space with a focus on trust and data sovereignty emerges as a promising area for further research.

A significant contribution of our research lies in the practical development and application of *visibility* in the freight transport sector. The data space, in particular, shows strong potential to enable the timely exchange of real-time and other critical data among trusted stakeholders, an essential component of synchromodality. Our case study reinforces this approach by demonstrating its successful implementation throughout the inland waterway transport operation and highlighting its applicability to other transport contexts.

For broader scenarios, the synchromodal data space provides flexibility and scalability through its building blocks (*data interoperability, data sovereignty and trust*, and *data value creation*), which can be developed and integrated according to the specific context and scale of the operation. As demonstrated in the use case implementation, not all building block elements were required, and certain framework components needed adaptation to align with stakeholder needs, such as harmonizing terminal nomenclature. In contrast, AIS data was integrated as-is due to its inherent characteristics; however, its use required specific conditions (data usage policies) to ensure compliance with GDPR.

Looking to the future, it is crucial to incorporate a broader range of technology stakeholders from the data space into the synchromodal concept. Their roles are vital in meeting the needs of systems like synchromodality. For example, we emphasize the importance of incorporating actors like *data space service providers, metadata brokers*, and *app* *providers*, and advocate for the integration of academic developments (e.g., quantitative models for service allocation, (re)routing problems, horizon control) with these actors in practical applications. Moreover, this aligns with the EU's strategic direction for data handling and sharing, underscoring the potential for enhanced collaboration among private entities and between the academic, governmental, and private sectors. We encourage researchers to explore the vast possibilities that a synchromodal data space offers for the future of logistics and transport.

CRediT authorship contribution statement

Juan Manuel Pulido: Writing – original draft, Writing – review & editing, Software, Methodology, Data curation, Conceptualization. **Ivan Cardenas:** Writing – original draft, Writing – review & editing, Supervision, Methodology, Conceptualization. **Valentin Carlan:** Writing – review & editing, Methodology, Conceptualization. **Tom Bergmans:** Writing – original draft, Software, Data curation. **Thierry Vanelslander:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A.1. IDSA approach applications for the Supply Chain segment

Application Name	Description	Stage	Entities (Country)
GlobShare	Secure Data Sharing of logistic events in the multi-modal steel supply chain	Committed	Globis (BE) Simis (BE) UCGroup (NL) Cabooter Terminals (NL) Renory Terminals (BE)
Würth C-Part Supply	Supply of Manufacturing Companies with C-Parts	Committed	Würth (DE)
Industrial Additive Manufacturing Services	Solving the Trust Issue in Distributed Production Networks	Pilot	IBM (DE) Thyssenkrupp (DE) Fraunhofer ISST (DE)
Horizontal Supply Chain Collaboration	Collaboration Digitised and trusted transparency of material flow in the full supply chain	Pilot	SICK (DE)
ONCITE	Sharing Data in the Supply Chain	Pilot	German Edge Cloud (DE)
AI.SOV	Sovereignty compliant exchange of AI results and information among trusted supply chain partners	Pilot	Cefriel (IT) Whirpool (EU) Inesctec (PT) Sonae Arauco (IT) Politecnico di Milano (IT)

Pilot: IDS-based solution has been implemented, and first prototypes have been tested in a use case pilot.
Case Committed: The scope of the use case, the value created, and the roles of the organizations involved have been identified. An approach for realizing the use case has been defined.
Elaborated from IDSA [41].

A.2. Profile of companies

To assess the companies' stance on adopting synchromodality, we employed the maturity model assessment developed by Alons-Hoen et al. [5]. We interviewed leading companies in the productive and supply chain sectors located in Belgium with operations at a European level. The interviews and workshops were held with LSPs, Shippers/Manufacturers, Terminal Operators, and Forwarders during the period from June 2022 to April 2023 (Table 5).

Table 5
Description of companies and maturity status on data exchange.

Role	Yearly Volume	Employees	Corridor	Modality Usage (rank %)	Planned Capacity	Data Exchange
Forwarder	> 6000 TEU	40	Worldwide	1. Road: 61–80 % 2. Barge: 1–20 % 3. Rail: 0 %	21–40 %	3
LSP	3000–6000 TEU	7500	Europe + Eurasia	1. Road: 41–60 % 2. Rail: 21–40 % 3. Barge: 1–20 %	41–60 %	4
LSP	> 6000 TEU	250	Worldwide 100 %	1. Road: 81- 2. Barge: 1–20 % 3. Rail: 0 %	61–80 %	4

(*continued on next page*)

Table 5 (*continued*)

Role	Yearly Volume	Employees	Corridor	Modality Usage (rank %)	Planned Capacity	Data Exchange
LSP	> 6000 TEU	2500	Worldwide	1. Barge: 41–60 % 2. Road: 41–60 % 3. Rail: 1–20 %	41–60 %	4
LSP	> 6000 TEU	600	EU-UK, PL-E	1. Road: 21–40 % 2. Barge: 21–40 % 3. Rail: 1–20 %	21–40 %	4
Shipper	> 6000 TEU	20,000	Europe	1. Road: 41–60 % 2. Rail: 21–40 % 3. Barge: 1–20 %	81–100 %	4
Shipper	5.5 Million Ton	6000	Europe	1. Road: 41–60 % 2. Rail: 21–40 % 3. Barge: 21–40 %	41–60 %	4
Shipper	> 6000 TEU	4500	Worldwide	1. Road: 41–60 % 2. Rail: 21–40 % 3. Barge: 1–20 %	81–100 %	3
Shipper	> 6000 TEU	8000	NL - BE - 100 % DE	1. Barge: 81- 2. Rail: 1–20 % 3. Road: 0 %	81–100 %	4
Shipping line	> 6000 TEU	550	Worldwide	1. Barge: 41–60 % 2. Road: 21–40 % 3. Rail: 1–20 %	61–80 %	4

Planned Capacity: Percentage of planned capacity based on forecast provided by another company or logistics associate.
Data Exchange: Maturity level in the data exchange element obtained from the maturity model assessment in synchromodality developed by Alons-Hoen et al. [5].

Data availability

The authors do not have permission to share data.

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