

Article

A Competency Framework for Human Interoperability in Data Spaces

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Abstract

The growing deployment of European Data Spaces requires more than advanced technical infrastructures; it also demands specialised human competencies to ensure interoperability, governance, and trust. This paper redefines organisational readiness as a key indicator of the transition from experimental deployments to large-scale, governed data exchange. Although technical solutions provide the necessary foundation, training is essential to ensure that the digital transition is supported by professionals capable of operating these ecosystems effectively. To address the research question, “Which competencies are required to enable data reuse within Data Spaces?”, with a specific focus on spatial data and Urban Digital Twins, this study proposes a hybrid methodology. This approach combines a top-down analysis of reference architectures (e.g., EIF and DSSC Blueprint) with a bottom-up diagnosis based on an expert-based qualitative survey. Preliminary results suggest that, although 58% of organisations identify technical integration between BIM and GIS as the main obstacle, 47% identify the shortage of specialised skills as the primary bottleneck preventing operational maturity. The analysis reveals a Maturity Plateau that hinders the transition from technical connectivity (Data Space Maturity Model Level 2) to full operational maturity (Level 3). To overcome this barrier, the study presents a convergence matrix based on the DIS4SME initiative, mapping knowledge gaps to a competency roadmap. This framework identifies urgent training needs in the semantic and legal domains, and provides an operational guide for supporting organisational maturity across Data Spaces and strengthening professional expertise.

Keywords: data spaces; human interoperability; urban digital twins; competency framework; data space skills; organisational readiness



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1. Introduction

In the context of the European Strategy for Data (<https://digital-strategy.ec.europa.eu/en/policies/strategy-data>), Data Spaces have emerged as a transformative socio-technical model designed to enable the secure, governed, and interoperable exchange of data [1]. By moving beyond traditional vertical silos, these federated infrastructures aim to create a European Data Union where data sovereignty and trust enable multiple actors to generate economic and strategic value without losing control over their assets [2].

To implement this framework, the European Commission has promoted sectoral Data Spaces and supported initiatives like the Data Spaces Support Centre (DSSC) (<https://data-spaces.eu/>).

[//dssc.eu/](https://dssc.eu/)) to establish common reference architectures and governance models. However, the existence of robust technical frameworks and regulations, such as the Data Governance Act, does not inherently guarantee effective interoperability or the successful execution of complex use cases [3,4]. A critical factor emerging in the consolidation of these ecosystems is organisational readiness: the multi-dimensional ability of an entity to transition from isolated data management to active participation in a federated data ecosystem. According to Weiner [5], organisational readiness for change is defined as a shared psychological state reflecting organisational members' commitment to and capability for implementing change. In the context of Data Spaces, organisational readiness extends beyond technological deployment and includes the availability of specialised competencies required to manage semantic alignment, governance mechanisms, and legal compliance.

The Data Space Maturity Model (DSMM) (<https://dssc.eu/space/B1/114131551/Data+Space+Maturity+Model>), developed by the DSSC, formalises the progression from initial experimentation to full ecosystem integration. According to this framework, organisations evolve through increasing levels of maturity, ranging from early awareness to fully operational participation in federated data ecosystems.

In particular, the transition from DSMM Level 2 (Technical Connectivity) to DSMM Level 3 (Full Operational Maturity) represents a critical shift where technical infrastructure alone is no longer sufficient. While Level 2 focuses primarily on establishing secure technical connections between participants, Level 3 requires the ability to manage semantic interoperability, governance mechanisms, and legal compliance across the data lifecycle. In this evolutionary phase, human interoperability represents the critical bridge, transforming basic technical connections into real-world operational value and sustainable federated governance. However, despite the increasing availability of connectors and federated infrastructures, many organisations remain unable to advance beyond pilot deployments. In practice, this results in a maturity gap between DSMM Level 2 and Level 3.

In this paper, we refer to this transition gap as a Maturity Plateau: a stage in which organisations have deployed the technical components required for data exchange but lack the competencies necessary to manage semantic interoperability, governance mechanisms, and legal compliance at scale. Understanding the causes of this plateau is therefore essential for enabling organisations to move from technical connectivity toward fully operational participation in Data Space ecosystems.

The implications of this transition are particularly evident in the domain of Urban Digital Twins (UDTs), where automated analysis and data reuse depend on professionals' ability to maintain interoperability mechanisms across the entire data life cycle. Despite the availability of mature standards (e.g., DCAT-AP (<https://op.europa.eu/en/web/eu-vocabularies/dcat-ap>)), INSPIRE (https://knowledge-base.inspire.ec.europa.eu/index_en), NGSI-LD (<https://ngsi-ld.org/>), structural barriers such as semantic heterogeneity and low metadata quality persist [6]. While technical connectors represent a significant advancement, they do not resolve the underlying challenges of semantic and legal alignment. As emphasised by the Joint Research Centre, success depends on the expertise required to harmonise data models and define meaningful usage contracts.

Currently, there is a significant gap in organisational preparedness that threatens to slow down or halt the consolidation of European Data Spaces. Although technical architectures and reference frameworks have reached a high degree of maturity, their practical implementation remains stuck in a phase of evolutionary stagnation, particularly in the transition from pilot projects to fully federated data ecosystems at DSMM Level 3 maturity. Several studies agree that the mere availability of interoperable infrastructures (such as connectors, catalogues, or federation services) does not, on its own, guarantee effective interoperability or sustainable data reuse [7,8]. This challenge highlights the urgent need for human interoperability, the specialised capacity of experts to translate abstract

standards into reliable, governed data flows. Existing educational programs, however, do not sufficiently address these hybrid skills, a limitation identified by both institutional actors (e.g., OGC Academy, DSSC Skills Board) and European projects like DIS4SME, which note the difficulty SMEs and administrations face in training profiles capable of validating complex datasets [9].

Against this backdrop, this article addresses the research question: “Which competencies are required to enable effective data reuse within Data Spaces?” In particular, this study aims to identify, classify, and systematise the knowledge and competencies needed to ensure interoperability in Data Spaces with a relevant spatial component. Using the domain of Urban Digital Twins (UDTs) as a primary case study, we propose a mixed methodology that integrates a top-down analysis of reference architectures with a bottom-up diagnosis based on empirical evidence from the DIS4SME project. The analysis identifies a critical bottleneck in organisational readiness between the Technical Connectivity level, characterised by experimental pilots, and the Full Operational Maturity level. The top-down component is based on an expert-based qualitative survey conducted as part of this study. Survey results indicate that organisations struggle to transition from isolated pilot projects to fully federated systems at DSMM Level 3 maturity due to structural gaps in semantic alignment and a lack of specialised personnel. Notably, 58% of respondents cited BIM/GIS integration as a primary technical barrier, while 47% noted a severe shortage of specific interoperability skills. The bottom-up approach draws on the empirical training outcomes of DIS4SME [9] to align these needs with practical educational responses. Based on these complementary approaches, this article provides a comprehensive roadmap for competency evolution, establishing human interoperability not merely as a supportive competency but as a formal and indispensable pillar of the data space architecture.

This paper makes three primary contributions to the emerging literature on Data Spaces. First, it conceptualises human interoperability as a distinct dimension of organisational readiness in federated data ecosystems. Second, it identifies a Maturity Plateau between DSMM Level 2 and Level 3, where technical connectivity exists but operational interoperability remains constrained by competency gaps. Third, it proposes a competency framework derived through a hybrid methodological approach that combines architectural analysis with empirical evidence from expert-based qualitative survey and training initiatives.

2. Background

2.1. Interoperability in Data Spaces

Interoperability is recognised as one of the fundamental pillars of Data Spaces. The DSSC Blueprint project [3] integrates both data interoperability and ecosystem-wide interaction, highlighting capabilities such as shared data models, standardised information exchange, and traceability mechanisms. Unlike traditional integration approaches, Data Spaces treat interoperability as a shared resource, achieved through common principles and standards.

The European Interoperability Framework (EIF) [10] provides a consolidated analytical framework to understand these dimensions, structured in four interdependent levels: Technical, Semantic, Organisational, and Legal Layers

Table 1 illustrates the correspondence between EIF levels and their operational role in Data Spaces. This correspondence highlights that interoperability is not a monolithic concept but a multi-layered enablement process. Each level provides a specific set of capabilities that, when combined, transform a simple data exchange into a governed, trustworthy ecosystem.

Table 1. Mapping EIF interoperability layers to data space functional capabilities.

EIF Level	Data Space Role	Enabled Operational Capability
Technical	Operational Foundation	Autonomous Connectivity: Deployment of secure channels, identity verification, and technical policy enforcement (PDP/PEP).
Semantic	Meaning Preservation	Asset Harmonisation: Advanced metadata structuring, ontology mapping, and cross-domain data consistency.
Organisational	Process Coordination	Workflow Orchestration: Business role alignment, multi-party agreement negotiation, and operational commitment formalisation.
Legal	Compliance & Trust	Regulatory Enforcement: Onboarding management, legal entitlement verification, and automated compliance (GDPR/Data Act).

While the architectural alignment is crucial for single deployments, the European strategy envisions a network of interconnected spaces. This introduces a second dimension of interoperability, shifting from the internal consistency of an ecosystem to the federation between diverse sectoral or territorial initiatives, as synthesised in Table 2.

Table 2. Taxonomy of Interoperability: Internal (Intra-DS) vs. Cross-Data Space (Inter-DS).

Type	Scope & Strategic Role	Key Functional Deliverables
Internal	Ensures consistent operations and governed interactions within a single data ecosystem.	Internal Control: Verifiable logging, incident detection, audit support, and internal policy monitoring.
External	Enables cross-domain federation, scalability, and interconnection of sectoral initiatives.	Ecosystem Federation: Cross-domain identity recognition, catalogue linking, and semantic bridge management.

2.2. The Role of Connectors and Their Limitations

A connector is the technical element that enables direct communication between participants in a data space. Functionally, it acts as the interface through which each organisation integrates into the ecosystem, acting as its technical representation and managing the application of policies, identities, attributes and authorisation decisions throughout the entire data exchange lifecycle with the data space [2]. Table 3 summarises its role across the EIF dimensions.

Table 3. Correspondence between interoperability layers and the connector.

Interoperability Level	Role of the Connector
Technical	Executes data exchange processes in a compatible manner across organisations with heterogeneous infrastructures and technologies, ensuring effective system-to-system communication.
Semantic	Interprets and applies policies, metadata, and usage constraints in accordance with shared vocabularies and information models, ensuring consistent understanding of the exchanged data.
Organisational	Enforces roles, attributes, and entitlements defined by the data space governance models, aligning interactions with agreed organisational arrangements.
Legal	Automatically applies the agreed contractual conditions and usage rules, ensuring compliance with applicable legal frameworks throughout the data exchange process.

However, the technical literature [3,7] warns that the mere deployment of connectors does not resolve challenges in semantic or legal interoperability. Harmonising data models, validating metadata, and defining complex usage contracts still rely heavily on the knowledge of the professionals involved [11]. While connectors can technically execute predefined rules, they do not define those rules nor ensure their semantic or legal correctness. This reveals a structural limitation: while technical architecture is mature, the human dimension remains the unresolved challenge that prevents full operational maturity [12]. The connector acts as an executor of predefined rules; however, the semantic alignment of datasets and the legal design of usage contracts remain high-level human tasks.

This limitation helps explain why many organisations achieve technical connectivity without reaching DSMM Level 3 operational maturity, despite deploying mature infrastructures. In this sense, connectors should be understood as a necessary but not sufficient condition for data space maturity. Their effectiveness is directly constrained by the organisational readiness of participating entities and the availability of specialised human competencies capable of translating abstract interoperability principles into governed and reusable data flows.

2.3. The Data Space Maturity Model and Organisational Readiness for Operational Maturity

The transition from traditional data silos to integrated European Data Spaces requires a structured evolutionary path. This progression can be framed through DSMM, which provides a multi-dimensional framework to assess an organisation's readiness to participate in sovereign, federated data ecosystems (see Figure 1).

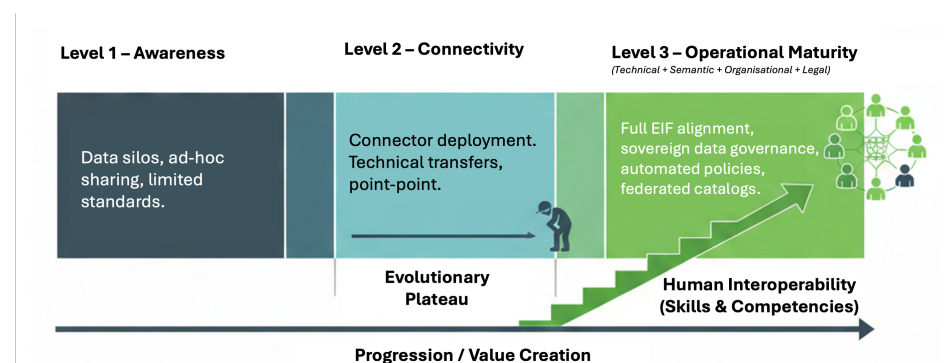


Figure 1. The Data Space Maturity Model: visualisation of the three evolutionary levels and the “evolutionary plateau” at DSMM Level 2, highlighting human interoperability as the driver for DSMM Level 3. The colours are used to improve the visual distinction between the three maturity levels.

The DSMM is typically organised into incremental levels, each requiring the consolidation of specific technical and human capabilities:

- Level 1 (Initial/Awareness): The organisation identifies the potential value of its data assets but operates in silos. Sharing processes are ad hoc, with limited understanding of interoperability standards or governance requirements.
- Level 2 (Experimental/Connectivity): This stage focuses on the technical deployment of connectors (e.g., IDS, Gaia-X). The organisation can establish point-to-point connections and execute technical transfers. However, many organisations reach an “evolutionary plateau” at this stage: while the physical infrastructure is present, they lack the multi-dimensional competencies required to manage the complexity of higher maturity levels.
- Level 3 (Operational/Trustworthy): At this stage, interoperability is achieved across all EIF layers. The organisation does not merely exchange data; it actively governs its

digital sovereignty, enforces automated usage policies, and participates in scalable, federated catalogs.

By adopting the DSMM, the metric for success shifts from “technical connectivity” to organisational readiness as a prerequisite for operational maturity. Organisational readiness is defined as the alignment between technological assets and a qualified human workforce capable of interpreting regulatory frameworks (e.g., Data Act, GDPR) and managing the semantic harmonisation of data (e.g., through spatial ontologies and advanced metadata standards).

In this context, the transition from DSMM Level 2 to DSMM Level 3 represents the primary hurdle for European SMEs. This transition does not simply depend on software updates, but rather the resolution of the critical competence gap defined in this paper as human interoperability. Without addressing this “missing middle,” organisations remain tethered to the experimental phase, unable to achieve the scalable and trustworthy participation required by the European Data Strategy. Addressing this ‘missing middle’ between DSMM Level 2 and DSMM Level 3 maturity is thus the central challenge for SMEs. This paper argues that human interoperability is the critical success factor for achieving DSMM Level 3 operational maturity, enabling full organisational readiness and providing the necessary competence-based roadmap to scale beyond the evolutionary plateau.

2.4. Skills in Data Spaces

2.4.1. The Need for Digital Skills

The successful deployment of Data Spaces in Europe does not depend solely on robust regulatory frameworks or advanced technical architectures. Although the existence of interoperable infrastructures (connectors, registries or federation services) is a fundamental prerequisite, empirical evidence shows that these conditions alone do not guarantee success. The full operational maturity of Data Spaces requires qualified human capital capable of applying, adapting and evolving these infrastructures in specific sectoral contexts. One of the most relevant application domains is spatial data, where interoperability poses unique challenges and opportunities, highlighting the need for standardised formats, semantic alignment and appropriate governance mechanisms to enable effective operational integration at DSMM Level 3 maturity [9].

Spatial datasets, such as satellite imagery, geolocated sensor data, and cadastral maps, are often governed by domain-specific standards and legacy infrastructures [13]. In this context, interoperability involves a holistic integration of such data across multiple thematic areas (environmental, urban, transport) and administrative levels [14].

The INSPIRE Directive (https://knowledge-base.inspire.ec.europa.eu/legislation/inspire-directive_en) (2007/2/EC) laid the foundations for the harmonisation of spatial data infrastructures in the EU [15]. The emergence of Data Spaces requires integrating spatial data with other domains. This requires a new set of skills related to metadata enrichment, semantic alignment, and multi-domain interoperability [16], anchored in the FAIR (<https://www.go-fair.org/go-fair-initiative/>) principles (Findable, Accessible, Interoperable, Reusable) [17].

The complexity of Data Spaces stems from their socio-technical nature, integrating technological, legal, organisational, and semantic dimensions. Although architectures such as IDS-RAM and the DSSC Blueprint address technical elements, challenges related to semantic heterogeneity, organisational fragmentation, and legal consistency remain [3].

Human interoperability, therefore, emerges as the key differentiating factor. Although technical mechanisms guarantee connection, only human expertise can transform that connection into a useful, reliable and governed data flow.

2.4.2. European Policies on Digital Skills

The observation that skills gaps are a structural brake on the data economy is directly linked to the European policy framework on digital skills. Several European initiatives, including the European Skills Agenda and the Digital Compass 2030, highlight the importance of advanced digital skills for the data economy.

These policies establish the foundation for professionals to operate within reliable data ecosystems, yet their real impact depends on implementation through specific sectoral initiatives.

These initiatives complement European digital competence frameworks such as DigComp, which provide a general structure for digital literacy and workforce capabilities [18]. However, Data Space ecosystems require more specialised competencies in areas such as semantic interoperability, data governance, and legal compliance. The framework proposed in this paper addresses these capabilities in the context of federated data ecosystems.

2.4.3. Connecting Skills Policy and Data Spaces

The synergy between digital skills policies and Data Spaces is reflected in projects like DS4Skills (<https://www.skillsdataspace.eu/wiki/>), which is pioneering a European data space dedicated specifically to competencies. It integrates information on skills, qualification frameworks and labour market needs within a federated ecosystem.

In parallel, the DIS4SME (<https://www.dis4sme.eu/>) project represents a significant example of practical implementation. It was designed to address the digital skills gap in SMEs regarding location data interoperability. Although DIS4SME was not originally conceived for the Data Space domain, its outcomes may be a strategic precursor for Data Space adoption, as the technical and organisational challenges faced by SMEs in daily data management directly mirror the requirements of federated data ecosystems. The project provides training pathways and micro-credentials that enable professionals to acquire advanced skills in standardisation, digital governance, and data reuse. It adopts a multi-level approach integrating technical skills (formats, APIs, catalogues, and open standards), organisational skills (governance management), and semantic interoperability (metadata management). The competencies developed within DIS4SME are therefore relevant for the implementation of Data Spaces, highlighting the importance of specialised skills for translating interoperability principles into operational practices and supporting organisational readiness.

2.4.4. A Methodology to Identify Skills for Data Spaces

Building on the role of specialised skills as enablers, it is necessary to quantify the distance between the existing expertise in SMEs and the complex demands of Data Space architectures. While projects like DIS4SME provide the “how-to” for data interoperability, the transition to Level 3 maturity requires a more granular understanding of where these skills are currently missing. Despite the strategic frameworks established by European policies and initiatives such as DIS4SME, there is still no systematic methodology that allows for the consistent identification, structuring, and prioritisation of the skills critical to the success of different Data Spaces. While technical architectures have well-defined guidelines for their design and deployment, the translation of these requirements into specific professional profiles and training needs remains fragmented and dependent on the domain or sector of application.

To bridge this gap, a structured methodology is needed to move from the abstract definition of “building blocks”, understood as the basic functional and organisational components of a data space (e.g., connectors, catalogues, identity services or governance mechanisms), to the operational maturity-oriented specification of functions, skills and

professional profiles. By integrating a top-down analysis of reference architectures with bottom-up empirical validation based on actual training outcomes, this study proposes a reproducible and transferable methodological framework that ensures that the human dimension of Data Spaces evolves in line with DSMM operational maturity, rather than focusing solely on technological deployment, avoiding mismatches between technical capacity and organisational readiness.

3. Methodological Approach

To evaluate organisational readiness for secure, automated, and legal compliant data exchange, the proposed methodology maps fundamental functional activities onto the Data Space Lifecycle. Organisational readiness is assessed using the DSMM. The analysis specifically focuses on bridging the “evolutionary plateau” between Level 2 (Technical Connectivity), where technical infrastructure has been deployed but remains limited to isolated pilot implementations, and Level 3 (Full Operational Maturity), where human interoperability enables the autonomous management of complex, federated data flows characteristic of DSMM Level 3 operational maturity.

To address this challenge, the study adopts a hybrid approach that integrates a top-down analysis establishing a theoretical benchmark of required competencies with a bottom-up diagnosis of current skill gaps within European organisations, supported by empirical evidence from the DIS4SME training program. This dual perspective is consistent with educational and competency frameworks that combine functional identification with empirical validation [19,20], ensuring that human interoperability effectively complements technical infrastructure [16]. This hybrid design follows a mixed-methods logic based on triangulation, where different sources of evidence—architectural analysis, expert-based qualitative survey, and empirical training outcomes—are combined to strengthen the robustness and validity of the findings [21]. By integrating theoretical models with practitioner perspectives, the study seeks to bridge conceptual and operational dimensions of competency development in Data Spaces.

Phase 1. Data Space Delimitation

The initial phase defines the scope of the application and operational context to ensure sectoral relevance, specifically selecting Urban Digital Twins and the built environment as the primary domains of investigation. Rather than focusing exclusively on technical processes, this stage identifies and characterises key stakeholders, including data providers, consumers, and intermediaries, to identify the relationships that dictate governance. By establishing this functional environment, Phase 1 provides the foundational logic for deriving the professional requirements and institutional arrangements necessary to sustain the ecosystem.

Phase 2. Functional Analysis

This phase identifies the operations required for secure data circulation by mapping them onto the Data Space Lifecycle. To establish a robust baseline, this study adopts the DSSC Blueprint v1.0 and the IDS-RAM as theoretical benchmarks. Each lifecycle stage is described through functional activities cross-referenced with the EIF layers. The primary output is the Competency Catalogue, a multidimensional structure linking technical building blocks (e.g., Connectors, Brokers) to the ideal professional competencies required for DSMM Level 3 operational maturity.

Phase 3. Top-down Requirements

Building upon the functional analysis, this phase tests the theoretical benchmark against professional reality. To assess these requirements, a structured questionnaire is

distributed to the specialised communities identified in Phase 1. The survey focuses on the functional activities of the Data Space lifecycle to identify knowledge gaps and the perceived barriers associated with the Maturity Plateau between experimental pilots and full operational interoperability. This process identifies the discrepancy between the ideal competency profile and practitioners' current expertise.

Data are collected through an online questionnaire distributed via LinkedIn by sharing a survey link with professionals working in the fields of Data Spaces and geospatial interoperability. Consequently, the study relies on a convenience sample of experts. Consistent with its expert-based qualitative design, the objective of the study is not to achieve statistical representativeness but to elicit informed expert judgements from professionals with direct experience in Data Space initiatives. Participation is voluntary, and participants are informed about the purpose of the study before accessing the questionnaire. Responses are collected anonymously, and no personally identifiable or sensitive personal data are collected or processed. The study does not involve any clinical, biomedical, or interventional procedures involving human participants, and participation is restricted to adults. Under the applicable Italian regulatory framework, prior ethical clearance is not required for this type of anonymous expert survey. Furthermore, in accordance with Recital 26 of Regulation (EU) 2016/679 (General Data Protection Regulation, GDPR), the anonymous information collected falls outside the scope of the GDPR.

Phase 4. Bottom-up Evidence

In parallel with the top-down diagnosis, the bottom-up analysis incorporates empirical evidence from ongoing capacity-building initiatives to examine how competencies are addressed in practice. Using the DIS4SME project as a primary reference, this phase provides empirical complement to the top-down approach by observing how competencies are addressed in real-world scenarios.

By mapping the requirements of SMEs and technical operators, training modules are framed within the Data Space lifecycle, ensuring that learning outcomes and the development of micro-credentials align with actual DSMM Level 3 operational challenges and market needs.

Phase 5. Cross-mapping and Convergence

The final phase systematically integrates the results from the top-down and bottom-up analyses in order to develop a competency matrix that can be applied to different Data Spaces. This phase aims to overcome the fragmentation between the theoretical and the empirical, offering a consolidated vision that serves both to guide training and to support decision-making in the area of digital skills policies.

The process culminates in the construction of a competency matrix, designed as a strategic roadmap for prioritising educational efforts and policy interventions. This tool facilitates the detection of training gaps across the EIF layers, highlighting specific areas where professional capacity falls short of architectural requirements. Finally, the analysis leads to the formulation of strategic proposals for action, such as the development of specialised learning modules and the promotion of micro-credentials to ensure the portability of acquired skills. In this way, the convergence phase ensures that human interoperability serves as the essential pillar for a sustainable, trustworthy, and fully operational European data ecosystem.

Table 4 provides a synthesis of the methodological framework, highlighting instruments, outputs, and strategic objectives.

Table 4. Methodological Framework: Instruments, Outputs, and Strategic Objectives.

Phase	Instrument	Primary Output	Strategic Objective
Data Space Delimitation	Stakeholder Mapping	Application Scope	Define boundaries and map governance relationships.
Functional Analysis	Functional Mapping (Top-Down)	Competency Catalogue	Establish the Theoretical Benchmark IF and IDS-RAM.
Top-down requirements	Structured Questionnaire	Gap Analysis	Identify the Maturity Plateau and the discrepancy between theory and practice.
Bottom-up evidence	DIS4SME Empirical Evidence	Practical Training Modules	Align learning outcomes and micro-credentials with real-world SME needs.
Cross-mapping and convergence	Cross-mapping & Synthesis	Competence Matrix	Integrate top-down/bottom-up data into an Operational Tool.

4. Results

4.1. Delimitation of the Data Space for Urban Digital Twins

The selection of the Urban Digital Twins (UDTs) as application domain is a strategic choice based on three fundamental aspects: political priority, cross-sectoral integration, and geospatial structural dependence.

First, UDTs represent an emerging political priority within the European Data Strategy, recognised for their potential to operationalise the “Twin Transition”, the simultaneous green and digital transformation of European cities [1]. Although a dedicated European data space for UDTs has not yet been fully established, the practical relevance of this approach is supported by large-scale initiatives funded under Horizon Europe and the Digital Europe Programme. Flagship projects such as DestinE (Digital Twins of the Earth) (<https://destination-earth.eu>) and DUET (Digital Urban European Twins) (<https://www.digitalurbantwins.com>) have demonstrated how digital twins can optimise resource use, anticipate climate-related risks, and substantially improve urban quality of life through data-driven decision-making.

Beyond political relevance, the UDT is selected for its cross-sectoral and interoperable nature. It acts as a strategic convergence point for multiple existing European sectoral Data Spaces, integrating diverse data streams to support complex urban simulations. Specifically, the UDT leverages the Green Deal Data Space for environmental and climate data essential for adaptation modelling [1], as well as the Mobility Data Space to incorporate transport flows for simulating sustainable mobility patterns. Furthermore, it draws on the Energy Data Space for building efficiency data critical to urban energy transitions [3], while emerging initiatives in the Built Environment Data Space provide the necessary link to BIM, cadastral data, and urban planning [22]. This cross-sectoral character makes the UDT the ideal environment to study the transition from Level 2 (Technical Connectivity) to Level 3 (Full Operational Maturity), as it demands the highest degree of semantic and legal harmonisation.

Finally, the motivation for focusing on the UDT lies in its structural dependence on a spatial dimension, which serves as the fundamental mechanism for domain integration. Geospatial data provide the foundational layer upon which different sectoral domains can be integrated, where OGC/INSPIRE standards and georeferenced geometries enable the integration of diverse sectors—such as energy, climate, and mobility—into a single, coherent analytical model. This reliance on the geospatial component grants the UDT a

distinct identity, differentiating it from other sectoral Data Spaces and providing a rigorous framework for defining the functional, semantic, and legal perimeters required for its operation. Overall, this delimitation provides a sound methodological justification for the study, allowing for a clear distinction between capabilities inherited from other sectors and those specific to the urban domain, thereby reinforcing the central role of geodata in complex urban environments.

Ultimately, this delimitation establishes not only a technical perimeter but also a cross-sectoral stakeholder ecosystem. By positioning the UDT at the convergence of the Green Deal, Mobility, and Energy Data Spaces, we identify the functional necessity for three core professional clusters:

This mapping ensures that the subsequent identification of gaps is rooted in the actual organisational roles active within the European data landscape

- **Data Providers:** These actors provide the essential spatial and real-time substrate. They typically include mapping agencies, sensor network operators (IoT), and utility companies (energy, water, and waste management) responsible for geospatial and sensor integration.
- **Technical Operators:** Represented by ICT departments, software providers, and research institutions, these stakeholders are tasked with maintaining technical building blocks, such as connectors, brokers, and simulation engines, ensuring seamless data interoperability.
- **Strategic Managers and Data Consumers:** This cluster primarily encompasses municipal departments (urban planning, mobility, environment) and public regulators. They govern the overarching policy framework and utilise federated data flows to support evidence-based urban decision-making.

4.2. Functional Analysis: From Architecture to Human Interoperability

The identification of competencies is derived from a functional analysis that moves beyond a purely technical view, linking architectural components to the human expertise necessary to govern them. To establish a rigorous baseline, this study adopts the DSSC Blueprint v1.0 as its theoretical benchmark, utilising the Data Space Lifecycle as the functional backbone to derive a granular Competency Catalogue.

4.2.1. Mapping IDS-RAM Architecture to Operational Functions

The proposed methodology adopts the International Data Spaces Reference Architecture Mode (IDS-RAM) [4] to bridge the gap between technical components and professional roles. Each technical building block was mapped to the specific expertise required to enable multidimensional interoperability and identified eight key functional activities.

- **DS Connector:** Requires skills in usage policy enforcement to enable secure data access and sharing.
- **Broker Service:** Necessitates expertise in federated metadata for data cataloguing and publication.
- **Vocabulary Provider:** Requires proficiency in ontologies and data mapping to support semantic modelling.
- **Identity Provider:** Links to legal competencies in trust, authentication, and identity management for usage agreements.
- **Clearing House:** Requires auditing skills to ensure traceability and data lineage.
- **App Store:** Involves competencies in service integration and data enrichment for orchestrating data flows.

4.2.2. The Five-Stage Operational Lifecycle

The Five-Stage Operational Lifecycle provides a structured framework to describe how data are prepared, shared, used and governed within a data space. This approach decomposes the complexity of federated ecosystems into clearly defined operational stages, facilitating both technical analysis and the identification of organisational and human requirements.

The definition of the Five-Stage Operational Lifecycle is not proposed as a new theoretical model, but as an operational synthesis of existing European frameworks for data sharing and interoperability. While reference architectures such as IDS-RAM, the DSSC Blueprint and Gaia-X describe the technical components and governance mechanisms of Data Spaces, they do not explicitly organise these elements along a temporal or operational sequence. This absence of an explicit lifecycle perspective complicates the identification of responsibilities, competencies and maturity gaps at different stages of data exchange.

To assess organisational readiness, these functional activities are organised into a Five-Stage Operational Lifecycle. This framework explicitly captures the transition from DSMM Level 2 (Technical Connectivity), where infrastructure exists but remains confined to isolated or experimental deployments, to DSMM Level 3 (Full Operational Maturity), in which human interoperability enables the autonomous and federated management of data flows. The proposed Data Space Lifecycle is designed to address this limitation by structuring data space operations into a sequence of stages that reflect how interoperability is achieved in practice. This approach is consistent with the European Interoperability Framework (EIF), whose technical, semantic, organisational and legal layers are progressively activated throughout the data exchange process rather than applied simultaneously. Similarly, the model operationalises the FAIR principles by translating abstract requirements for findability, accessibility, interoperability and reusability into concrete operational stages. Figure 2 illustrates the Five-Stage Operational Data Space Lifecycle adopted in this study. It describes how data assets move through successive operational stages within a Data Space ecosystem, linking technical processes with the competencies required to achieve DSMM Level 3 operational maturity.

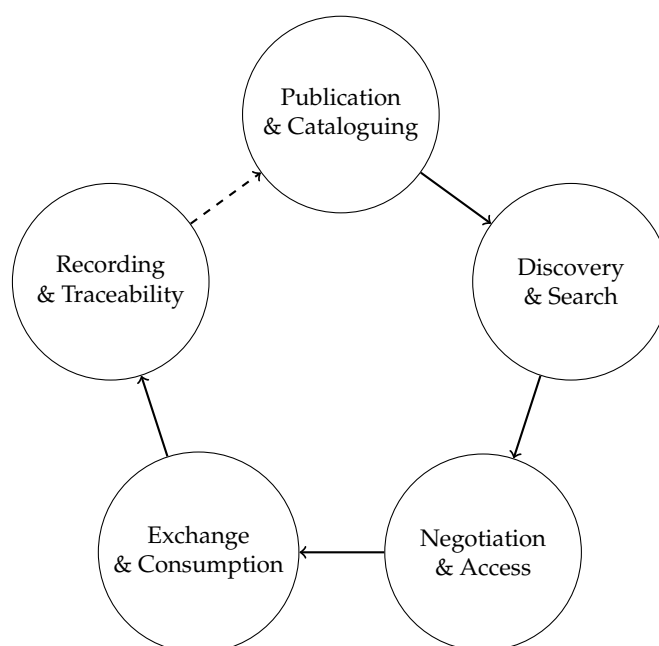


Figure 2. Five-Stage Operational Lifecycle of Data Space interactions. The dashed arrow indicates that the lifecycle may restart from the publication stage, although this transition is not necessarily automatic.

The five stages of the lifecycle are as follows:

1. **Publication and Cataloguing.** The focus is on the provider's ability to describe assets using standards. In this initial stage, the Data Provider prepares assets through Data Transformation and Harmonisation and Data Cataloguing and Publication. This involves organising datasets using standardised metadata (e.g., DCAT-AP) and common semantic models. By registering these assets in a federated Broker, the provider ensures that the data is ready for the ecosystem before its formal release.
2. **Discovery and Search.** Emphasis is placed on the consumer's capacity to navigate shared vocabularies and Linked Data principles. Consumers locate relevant data products using discovery services. This phase relies heavily on Semantic Modelling to ensure domain compatibility. Through federated access mechanisms, users can query and discover available services without compromising the provider's sovereignty, ensuring that the search process is both transparent and interoperable.
3. **Negotiation and Access:** Once data is located, parties establish the terms of use through Defining Usage Agreements. This phase bridges the legal and organisational dimensions by defining standardized contracts, licenses, and access policies. During this step, the Identity Provider validates credentials, ensuring that all transactions comply with regional legislation (such as GDPR) and that participants accept the shared governance rules.
4. **Exchange and Consumption:** The technical realization of the data flow occurs here, materializing the information transfer between infrastructures. It encompasses Data Access, Data Sharing with Third Parties, and Orchestrating Data Flows. Using IDS Connectors, the ecosystem executes secure transfers under strict access control policies, occasionally utilizing certified applications from an App Store to process or transform data at the point of use.
5. **Recording and Traceability:** The final phase focuses on Ensuring Traceability and Data Lineage to maintain trust and accountability. Every transaction is recorded and audited by a Clearing House to verify data provenance and regulatory compliance. This persistent monitoring ensures that data governance is maintained throughout the entire lifecycle, providing a transparent audit trail for all participants.

By consolidating these perspectives, the Five-Stage Operational Lifecycle provides a coherent analytical framework that bridges architectural descriptions and operational reality. More importantly, it enables the systematic mapping of human competencies to specific lifecycle stages, thereby supporting the assessment of organisational readiness and the identification of skills gaps that hinder the transition from experimental pilots to fully operational Data Spaces.

4.2.3. Competency Catalogue

The synthesis of this functional mapping results in the Competency Catalogue (Table 5).

Table 5. Competency Catalogue: the Theoretical Benchmark mapping Functional Activities and EIF Layers to Human Interoperability Skills.

DS Life Cycle Phase	Functional Activities & EIF Layers	Skills
Publication and Cataloguing	Data Cataloguing and Publication; Data Transformation and Harmonization. (Technical & Semantic Layers)	• Proficiency in applying metadata standards such as DCAT, Dublin Core, and ISO 19115. • Ability to use data discovery and cataloguing tools (CKAN, DataHub, Amundsen, Apache Atlas). • Skills in integrating data catalogues through APIs and interoperable interfaces. • Knowledge of data publication principles (FAIR, Linked Open Data, Open Data). • Ability to perform data mapping across heterogeneous sources. • Competence in data modelling using interoperable formats such as JSON, GeoJSON, and XML.
Discovery and Search	Semantic Modelling. (Semantic Layer)	• Knowledge of sector-specific ontologies for data discovery. • Ability to apply and interpret standard vocabularies shared across domains. • Skills in using linked data principles to support semantic interoperability.
Negotiation	Define Usage Agreements and Exchange Conditions. (Legal & organisational Layers)	• Understanding of the Data Governance Act, Data Act, and Open Data Directive. • Ability to ensure compliance with GDPR in data access and exchange scenarios. • Competence in licensing and rights management frameworks (e.g., Creative Commons).
Exchange and Consumption	Data Access; Data Sharing with Third Parties; Orchestrating Data Flows. (Technical Layer)	• Knowledge of standard data models, such as INSPIRE, OGC, and Open BIM. • Proficiency in formats and protocols (ISO/IEC 11179, W3C standards, RDF, IFC). • Ability to design and consume APIs and data access protocols. • Operational knowledge of IDS Connectors and Brokers. • Competence in data integration and ETL/ELT processes. • Experience with workflow orchestration tools and federated data access.
Recording and Traceability	Ensuring Traceability and Data Lineage. (Technical & organisational Layers)	• Competence in using data lineage tools and frameworks. • Ability to operate logging and monitoring systems for data exchanges. • Knowledge of database formats and metadata technologies supporting traceability and auditing.

In line with the methodology described in Phase 2, this catalogue serves as the theoretical benchmark for the study, establishing the ideal set of human skills required to operate a federated ecosystem. By cross-referencing lifecycle stages with functional activities and EIF layers, the catalogue identifies the human interoperability requirements necessary to bridge the gap between technical connectivity (DSMM Level 2) and full operational maturity (DSMM Level 3).

4.3. Top-Down Requirements: Identifying the Maturity Plateau

To test the theoretical benchmark defined in Phase 2 against professional reality, a structured questionnaire was distributed to the stakeholder ecosystem identified in Phase 1. The results reveal a significant discrepancy between technical availability and human readiness, confirming the existence of a Maturity Plateau that hinders the transition from DSMM Level 2 (Technical Connectivity) to Level 3 (Full Operational Maturity). The objective of this analysis is to empirically examine the existence of the Maturity Plateau hypothesised in the conceptual framework. Specifically, the survey investigates whether organisations that have achieved technical connectivity still face barriers in progressing to DSMM Level 3 operational maturity due to gaps in human interoperability competencies.

The primary investigative tool was a structured questionnaire built upon the eight functional activities identified and hierarchically mapped to the five stages of the Data Space Lifecycle. The survey was distributed among specialised professional communities and key European initiatives, including the Green Deal Data Space, DIS4SME, the International Data Spaces Association (IDSA) (<https://internationaldataspaces.org/>), the Open Geospatial Consortium (OGC) (<https://www.ogc.org/>) and the Building Digital Twin Association (BDTA) (<https://buildingdigitaltwin.org/>).

The survey addressed critical indicators such as familiarity with interoperability tasks, existing training availability, perceived barriers to implementation, and specific educational needs. This top-down diagnosis allows for the identification of specific knowledge gaps—areas where the current expertise of practitioners falls short of the theoretical requirements established in the Competency Catalogue (Table 5). In accordance with open science principles, both the survey instrument and the anonymized results are published on Zenodo <https://zenodo.org/records/16908881> to ensure transparency and reproducibility.

4.3.1. Sample Composition and Professional Readiness

The expert panel consisted of 19 participants. This sample size aligns with established qualitative research standards for highly specialized domains, where pilot assessments typically range between 15 and 24 respondents [23]. The diversity of expertise represented within the panel of the profiles provides significant analytical value, ensuring a balanced coverage of technical, policy, and operational areas. Corresponding questionnaire numbers are indicated in brackets below. Given the exploratory nature of the study and the specialised character of the Data Space ecosystem, the survey was designed as an expert assessment rather than a large-scale statistical study. While the sample provides valuable qualitative insights into emerging competency gaps, future research should extend the analysis through broader quantitative validation across different sectors and organisational contexts.

The participants represent a diverse organisational spectrum: universities and research centres (7), private companies (3), local or regional administrations (3), national public administrations (3), SMEs (2), and NGOs (1) (Q1). Geographically, the distribution illustrates a broad European diversity, with significant contributions from Southern and Western Europe (Spain, Italy, Belgium) and emerging insights from the Northern and Central regions (Netherlands, Finland, Germany) (Q6). This spatial spread is critical, as interoperability challenges are often influenced by varying national regulatory frameworks and local governance maturity.

Consistent with the methodology, the study adopts a professional cluster perspective to reflect how responsibilities are distributed in real-world organisations (Q5). The cohort included Strategic Managers (26.3%), while the remaining participants were divided between Researchers and Technical Operators. In this analysis, Researchers are functionally mapped to either Technical Operators or Strategic Managers, depending on their specific involvement in either infrastructure development or governance and policy-making within their respective projects. Functional roles identified (Q2) include Data Providers (BIM, cadastre, sensor data), Technical Operators (connectors and brokers), and Policy-makers (smart city managers), primarily focused on urban planning, mobility, and energy (Q3).

4.3.2. Analysis of Expertise and Knowledge Gaps

The analysis of participant expertise (Q11–Q13) reveals a hierarchy of skills that confirms the existence of the Maturity Plateau at DSMM Level 2. Respondents reported high familiarity with foundational activities: Data Access from heterogeneous sources (14), Data Transformation and Harmonisation (13), and Data Cataloguing and Publication (12). These activities, centred on metadata standards and FAIR principles, represent the established technical connectivity layer (Level 2) (Q7).

By contrast, a significant competence gap emerges as the requirements shift toward the more advanced layers of the European Interoperability Framework (EIF). Within the Semantic Layer, only a minority is involved in the definition or use of semantic models (7) or linked data principles (Q11), suggesting that automated data interpretation remains a critical hurdle. More pronounced gaps are observed in the organisational and legal layers, specifically regarding Data Governance and Sovereignty. Activities such as defining usage

agreements and exchange conditions (6) are largely confined to public administration profiles, leaving other clusters with low familiarity regarding the Data Governance Act or GDPR compliance (Q11, Q12). This deficit extends to advanced Data Sovereignty tasks, such as ensuring traceability and data lineage (5) or the orchestration of data flows (4) in federated architectures, which are the least represented across the cohort (Q11).

The self-assessment (Q9, Q13) confirms this trend: most respondents positioned themselves at a “medium” level of expertise, with low familiarity specifically in semantic modelling and flow orchestration. These findings suggest that while the infrastructure for Data Spaces is emerging, the human capacity to operate distributed governance and legal compliance remains the primary bottleneck for achieving DSMM Level 3 operational maturity.

4.3.3. Detailed Skill Requirements and Barriers

To quantify the human interoperability layer, respondents (Q14–Q21) identified the specific skills and knowledge deemed essential for each functional activity of the Data Space Lifecycle (Table 6). These eight questions were formulated in a multiple-choice format (check-all-that-apply), allowing respondents to select all applicable requirements. Results are calculated based on the frequency of selection for each item, with unselected options treated as null responses. Overall, the findings reveal a clear hierarchy of perceived needs, where foundational technical skills are well-recognised, but advanced governance and semantic competencies remain elusive.

Table 6. Skills and knowledge deemed necessary by respondents to the questionnaires.

Activity	Skill	Responses
Data Cataloguing and publication	Metadata standards (DCAT, Dublin Core, ISO19115)	15
	Data catalog integration (API, ...)	14
	Standards for Data Publication (FAIR, LOD, Open Data)	12
	Data Discovery and Cataloguing Tools (CKAN, DataHub, Amundsen, Apache Atlas)	6
	XML	1
	GeoDCAT-AP 3.0	1
Data transformation and harmonization	Data mapping from different sources	17
	Data modelling (JSON, GeoJSON, XML)	14
	SQL	1
	organisational change management	1
Semantic modelling	Use of standard vocabularies	15
	Linked data	12
	Knowledge of sectorial ontologies	11
Define usage agreements and exchange conditions	Data Governance Act, Data Act, Open Data Directive ...	14
	Licensing and rights management (e.g., Creative Commons)	10
	GDPR	10
Data Access (from heterogeneous sources)	JSON, XML, CSV, RDF, IFC	15
	APIs and data access protocols	15
	OGC standards	13
	Formats and protocols for data exchange (e.g., ISO/IEC 11179, ISO 19115, W3C standards)	12
	Open BIM	12
	Standard data model (INSPIRE)	11
Data sharing with third parties	Connectors	16
	Brokers	5
	Governance	1
Orchestrating data flows in a data space	APIs and Data Services	17
	Data Integration & ETL/ELT	12
	Workflow Orchestration Tools	7
	Federated Data Access	6
Ensuring traceability and data lineage	Knowledge of Database Formats and Metadata Technologies	17
	Data Lineage Tools & Frameworks	9
	Logging and Monitoring Systems	8

Note: Percentages may sum up to more than 100% due to the multiple-choice nature of the questions.

When asked about barriers (Q14), the lack of technical and legal skills (14 mentions) was identified as the predominant factor, far exceeding technological limitations. This confirms that the bottleneck is human rather than infrastructural. Consequently, most initiatives (Q25) remain in the pilot or experimental phase, often linked to research projects (e.g., AD4GD, USAGE), lacking the long-term institutionalization required for DSMM Level 3.

4.3.4. Training Preferences and Certification Needs

To address the identified gaps, the survey explored the preferred learning modalities and the perceived value of certification. Regarding training formats (Q23), participants expressed a strong inclination toward flexible, application-oriented learning: self-paced online technical courses and hands-on practical workshops with real use cases were the most selected options (13 mentions each). This preference suggests that traditional, theoretical academic lectures are seen as less effective for the fast-evolving requirements of Data Spaces.

Furthermore, the demand for formal recognition is significant: 58% of respondents (Q24) indicated the need for some form of certification (including certificates of achievement, national certifications, or micro-credentials) to validate their expertise. Although interest specifically in “micro-credentials” is still emerging, the overall data reflects a clear market need for standardised professional validation. These insights provide the foundational requirements for designing the training modules discussed in the subsequent phase of this study.

4.3.5. Readiness Evaluation

The empirical results of the questionnaire (Q14–Q21) provide substantial evidence of the evolutionary plateau described in the methodological framework. By analysing the current operational capacity of respondents, the study identifies a critical limiting factor that prevents the transition from technical deployment (DSMM Level 2) to full ecosystem participation (DSMM Level 3).

The relationship between the strategic importance of Data Spaces and actual professional readiness is particularly revealing. As shown in Table 7, while a vast majority of organisations recognize federated data sharing as a high strategic priority (Q25), this perception does not translate into operational capability. This discrepancy confirms that the human factor is the primary barrier: while 58% of respondents are still navigating technical hurdles such as BIM/GIS integration and basic data modelling (typical of Level 2), nearly half (47%) report a severe lack of the advanced interoperability skills required for DSMM Level 3.

Table 7. Mapping of Survey Results (Q14–Q21) to Data Space Maturity Model (DSMM) Levels.

DSMM Level	Operational Status (Q14–Q21)	Key Skill Gap Identified	Survey Correlation
Level 2	Deployment of connectors; focus on isolated pilots and 1-to-1 data sharing.	BIM/GIS integration and basic technical data modelling.	58% cite BIM/GIS integration as a primary technical hurdle.
Level 3	Automated negotiation; federated governance; human interoperability.	Semantic alignment, legal policy automation, and trust framework management.	47% report a severe lack of these specific interoperability skills.

This 47% skill gap represents the “missing middle”—the hybrid expertise that combines technical mastery with legal, organisational, and semantic governance. Without

addressing this gap through the Competency Catalogue (Table 5), organisations remain stuck in an experimental loop of isolated pilots. These findings demonstrate that human interoperability is the decisive variable in the organisational readiness equation; it is the necessary bridge to move from the current technical connectivity to a scalable, trustworthy, and fully operational European data ecosystem.

4.4. Bottom-Up Evidence: The DIS4SME Capacity Building

The findings from Phase 3 act as a requirements document for capacity-building. Since 58% of respondents identified the integration of BIM/GIS as a technical hurdle and 47% reported a severe lack of semantic and legal skills (Q26), Phase 4 explores how these needs are addressed through the DIS4SME (<https://www.dis4sme.eu/>) (Data Interoperability Skills for SMEs) project. This phase shifts from the “what is missing” to “how to fill the gap” using empirical evidence from a large-scale European training initiative.

DIS4SME provides modular training in advanced technologies, specifically geospatial data interoperability. The curriculum includes ten free specialised courses organised in four Business Case Studies (BCSs) and horizontal courses on transversal aspects of Location Data Interoperability. The training offers distinct paths for managers (strategic innovation and data-driven decision-making) and technicians (practical implementation). Delivered online in asynchronous self-learning mode via Moodle platforms hosted by GISIG (<https://www.dis4sme.eu/courses/>) and by OGC Academy (<https://academy.ogc.org/login/index.php>), the courses utilise micro-credentials (digital badges) to validate job-relevant skills. To maximise impact, these “Training Actions” were localized, translated, and validated through pilot sessions across different countries [9].

4.4.1. Curriculum Design: Aligning EQF and Bloom’s Taxonomy with Data Space Needs

The curriculum is based on the concept of Learning Outcomes (LOs), defining learner expectations across knowledge and skills. By applying Bloom’s Taxonomy [31], the project distinguishes between foundational knowledge and the advanced digital application required for DSMM Level 3. Through an iterative co-design process involving over 100 survey responses and 20 expert interviews, the curriculum was structured into two operational layers: the horizontal layer referred to transversal skills (Digital Transformation, metadata, and interoperability); the vertical layer which refer to sector-specific applications, including a dedicated course on 3D, BIM, and Digital Twins for Urban Planning, which addresses the specific “stress test” of spatial data integration.

Courses delivered as different training actions are organised into lectures, which deliver the instructional materials necessary to achieve a total of 61 LOs. Detailed information on LOs and lectures is provided on Zenodo (<https://zenodo.org/records/18457062>).

The project’s modular, hands-on training approach, focusing on QGIS tool, JSON data format, and OGC standard framework, is not merely an educational exercise. It is a strategic effort to build the human interoperability layer. By bridging technological, regulatory, and semantic gaps, DIS4SME provides the practical evidence that targeted capacity building is the only viable path to move SMEs from isolated, manual data practices to the automated, trusted environment of a DSMM Level 3.

4.4.2. Effectiveness and Strategic Impact: Closing the Readiness Gap

The effectiveness of the DIS4SME program in bridging the identified professional gaps is validated by the evaluation of 19 distinct training actions. An analysis of 157 participant responses (representing a 33% response rate) demonstrates a significant shift in competency levels, with a marked progression from “Basic” toward “Intermediate” and “Advanced” proficiency. This measurable growth is complemented by a nearly 100% satisfaction rate

(“Satisfied” or “Very Satisfied”), confirming the curriculum’s alignment with the high-level demands of the digital market.

Operationalizing the European Data Strategy. Beyond numerical results, the strategic impact of DIS4SME lies in its ability to translate the high-level objectives of the European Data Strategy into the daily operational practices of SMEs. By embedding open standards (INSPIRE, OGC, ISO) and FAIR principles into the learning pathways, the program ensures that the acquired skills are scalable and interoperable within the broader European data ecosystem.

From passive users to active providers. The sustainability of this approach is rooted in the enhancement of the digital autonomy of enterprises. By equipping professionals with the tools to manage data ecosystems and improve process efficiency, DIS4SME courses contribute to transforming SMEs from passive data consumers into active participants and intermediaries in the Data Space ecosystem.

Long-term competitiveness and the Green Deal. Finally, this capacity-building effort ensures that regulatory compliance—often perceived as a burden—becomes a competitive advantage. The ability to operate within federated data ecosystems enables sustainable innovation in line with the resource efficiency goals of the European Green Deal. Ultimately, DIS4SME indicates that addressing the “human factor” is the most effective strategy for guaranteeing the long-term competitiveness of European SMEs in the global data economy.

4.5. Convergence: Cross-Mapping and Gap Analysis

This phase integrates the top-down diagnosis (functional activities) with the bottom-up empirical evidence (DIS4SME training). The purpose of this convergence is twofold: first, to establish a Competency mapping matrix linking functional activities to current competency levels; second, to identify structural training gaps for the transition to DSMM Level 3.

4.5.1. Mapping SME Gaps to the Data Space Lifecycle

Although the DIS4SME survey and interviews focused on geospatial interoperability challenges for SMEs, the results closely align with the activities and stages identified in the Competency Catalogue. Analysing these learning needs through this lens reveals significant overlaps, suggesting that the project’s LOs potentially address gaps common to both scenarios.

According to DIS4SME users, European SMEs face a highly fragmented geospatial data landscape, where 70% struggle with incompatible formats and 55% encounter mismatches in coordinate systems or projections. Together with incomplete metadata and limited documentation, these issues complicate data cataloguing and make publication error-prone. Data transformation is another major bottleneck, with 50% of organisations reporting semantic or schema harmonisation problems, compounded by limited ETL expertise: 34% of respondents have no experience with tools such as FME, GDAL, or HALE, while only 14% consider themselves experts. Discoverability is also impaired, as 50% of participants report semantic inconsistencies and naming differences that reduce dataset visibility, in a context where shared vocabularies and semantic modelling skills remain scarce. Legal and organisational constraints further affect data use, with 29% of SMEs reporting security or intellectual property issues and 56% facing licensing or access restrictions, often due to limited awareness of GDPR and IPR obligations. Access and collaboration remain problematic for 56% and 40% of respondents, respectively, mainly because of restrictive licenses, missing shared APIs, and a lack of standardised harmonisation procedures. At the operational level, 64% experience difficulties integrating tools and platforms within Data Spaces, reflecting low automation and limited readiness for AI-driven processes.

Traceability and data lineage are largely overlooked, with most companies relying on informal practices rather than structured systems. Overall, more than half of the surveyed SMEs experience interoperability issues throughout the data value chain, highlighting how fragmentation, weak standardisation, and limited skills continue to constrain the effective exploitation of geospatial data.

4.5.2. DIS4SME Coverage and Gaps Analysis

The following cross-mapping, which provides an ex-post analysis of the DIS4SME questionnaires from a Data Space perspective, empirically confirms the alignment between bottom-up user needs and the top-down methodological approach. By cross-referencing the required skills identified in the top-down diagnosis (Table 6.) with the curriculum's 61 LOs, and applying Bloom's Taxonomy, we assessed the cognitive depth across the data lifecycle. Competence levels were categorized into Basic, Intermediate, and Advanced, reflecting the depth of cognitive engagement required: from conceptual awareness (Basic) to technical implementation (Intermediate) and strategic orchestration (Advanced). It should be highlighted that the DIS4SME curriculum was specifically tailored as a series of short courses for SMEs; therefore, it does not aim to cover all the knowledge and skills required to fully operationalise a Data Space. Instead, it focuses on delivering the most relevant competencies that fit the nature of SME-oriented professional development.

Publication and Cataloguing (8 LOs). This phase balances theory and practice, focusing on metadata standards and the FAIR principle. At the basic level, the curriculum covers understanding the FAIR principle for data management. The main emphasis shifts to the Intermediate level, where practical skills are developed in the application of metadata standards (ISO, DCAT, GeoDCAT-AP) and in data mapping and conversion techniques (e.g., FME, IFC/GIS formats) for data harmonisation. The Advanced level covers the ability to create and validate INSPIRE-compliant metadata.

Discovery and Search (24 LOs). This is the most covered area of DIS4SME, with 22 LOs at the Basic level, dedicated to building a robust conceptual framework for interoperability and semantic search. The Basic coverage is maximal, concentrating on the fundamental concepts of interoperability (semantic, technical), the principles of the EIF, the introduction to Data Spaces, and sectoral ontologies (such as BIM and Digital Twins). The Intermediate level integrates this framework by covering the detailed analysis of standards and their relationships within the BIM and 3D GIS worlds. This phase has no explicit coverage at the Advanced level.

Negotiation (6 LOs). This phase focuses on the regulatory and strategic framework required to define data usage and exchange agreements. Coverage is primarily at the Basic level, where DIS4SME includes understanding the EU regulatory framework (such as GDPR, Data Governance Act, and Data Act) and identifying managerial challenges related to interoperability. There is no specific training at the Intermediate level. The Advanced level develops the critical ability to evaluate the strategic impact of interoperability policies on organisational Digital Transformation.

Exchange and Consumption (21 LOs). As the second main focus, this phase is oriented towards the practical application, integration, and orchestration of data flows through standards and services. At the Basic level, training covers understanding the principles of OGC and API services and identifying DT platforms and their advantages. The Intermediate level develops operational competencies in the use of OGC Web Services, the integration of complex data (CityGML, BIM), and workflow orchestration (ETL/ELT). The Advanced level addresses the evaluation of the most complex challenges related to BIM-GIS interoperability and integration.

Recording and Traceability (2 LOs). This phase has the lowest coverage, but it is balanced (one LO per level), focusing on data lineage and interoperability challenges in complex systems. The Basic coverage provides an understanding of the specific interoperability challenges for building and maintaining Digital Twins. The Intermediate level develops the practical ability to handle different formats and coordinate systems to overcome interoperability problems. The Advanced level covers the evaluation of specific tools and software for the exchange and visualization of BIM and GIS data, which are essential for traceability and data lineage.

The mapping results summarised in the Heatmap (in Figure 3), show the distribution of coverage instances (LOs) by Data Space Phase and Competence Level. As illustrated in the table, the high concentration of LOs at the Basic level (40 total instances) and the clear dominance of the Discovery and Search phase (24 instances) confirm that DIS4SME places absolute priority on establishing a solid conceptual and semantic foundation necessary for interoperability in the Data Space. The 16 Intermediate instances, largely concentrated in the Publication and Cataloguing and Exchange and Consumption stages, reflect an effective development of the operational and technical skills necessary for the practical application of standards.

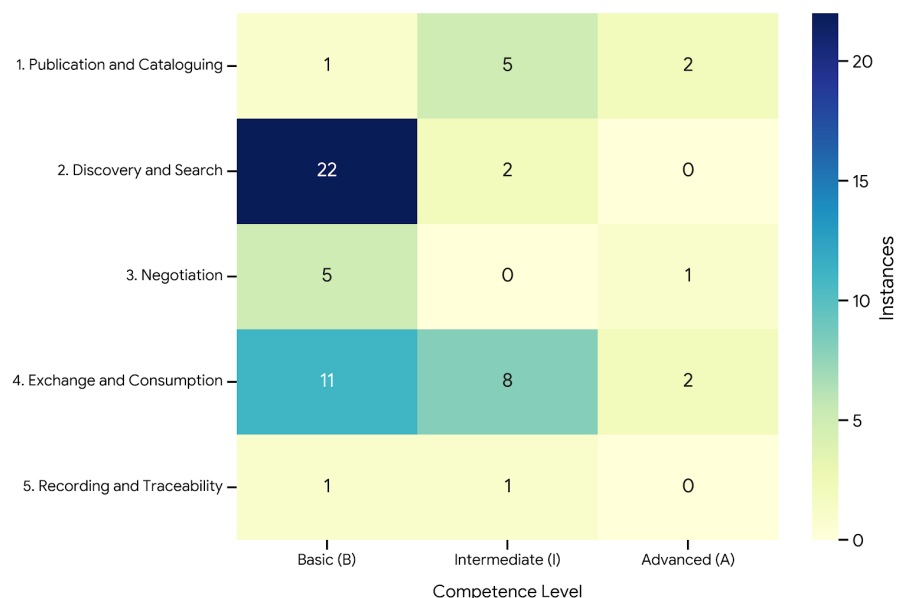


Figure 3. Heatmap of Learning Outcome (LO) coverage across Data Space operational phases. The color intensity represents the frequency of LOs, highlighting a primary concentration in “Discovery and Search” at the Basic level and a more distributed pattern in “Exchange and Consumption.”

Despite its solid conceptual foundations (validated by 40 Basic-level LOs), the DIS4SME curriculum has some gaps, particularly in areas of technical specialisation, specific operational tools and advanced regulatory management. In the Publication and Cataloguing phase, instruction is strong on metadata standards (ISO/DCAT) but lacks coverage for the integration of Data catalog tools (e.g., CKAN), low-level formats (XML, SQL), and organisational change management. The Discovery and Search phase, despite its LO dominance, exhibits a missing specific focus on the Linked data paradigm [24], essential for advanced semantic interconnection. The Negotiation phase presents the greatest compliance risk: coverage is limited to the general regulatory framework (DGA/Data Act), with a total absence of specific LOs on GDPR and Licensing and rights management. In the Exchange and Consumption phase, while OGC and ETL competencies are well-developed (Intermediate), there is an absence of skills related to advanced connectors (Connectors,

Federated Data Access, Brokers) and distributed data governance. Similarly, the Recording and Traceability phase shows a deficit in active monitoring and logging tools.

Table 8 synthesises the alignment between competency demand, as derived from the Phase 3 top-down survey results, and the available training supply and gaps identified in the Phase 4 DIS4SME framework. By synthesising these dimensions, the competency matrix (Table 8) goes beyond a purely descriptive overview and functions as a foundation for a roadmap for human interoperability. It identifies high-priority areas, such as Advanced Semantic Modelling and Federated Access, where market complexity and technical–legal friction are highest. Addressing these focal points through targeted training is the prerequisite for overcoming the current evolutionary plateau and enabling the transition to DSMM Level 3.

Table 8. Competency mapping matrix Aligning Survey Demands with Curriculum Supply.

Data Space Lifecycle Phase	Competences Demand (Phase 3)	Curriculum Offer (Phase 4)	Residual Training Gaps
Publication and cataloguing	Moderate gap (23%) in data harmonisation and transformation.	Focuses on advanced practical application, including metadata standards (DCAT/INSPIRE) and data harmonisation.	Limited training on data encoding, cataloguing tools, and organisational change management.
Discovery and search	Largest gap (25%), especially in advanced semantic alignment tasks.	Focuses on building a solid conceptual and semantic foundation (EIF principles, BIM/DT ontologies) for knowledge assimilation.	Educational gap on practical Linked Data use within semantic interoperability training.
Negotiation and access	Smallest gap (13%) concerning usage rights and licensing practices, but with low urgency.	Covers understanding of the EU regulatory framework and evaluation of policy impacts on the organisation.	Missing focus on applying data usage and licensing rules.
Exchange and consumption	Operational challenges (21%) in sharing data and workflow orchestrating.	Emphasises practical technical abilities: OGC APIs, data integration (ETL/ELT), and workflow orchestration in Digital Twin environments.	No explicit focus on federated data access mechanisms or real-time sharing governance.
Recording and traceability	Notable gap ($\approx 19\%$) in implementing lineage and traceability systems.	Focuses on principles of traceability and data lineage, with basic practical applications.	Lack of specific training on logging and monitoring systems for reliable, federated data flows.

4.5.3. Educational Responsiveness

The analysis of training and certification preferences (Q23, Q24, and Q27) reveals a high degree of synergy between professional market demands and the proposed capacity-building strategy. This alignment is a critical indicator of organisational readiness, as it demonstrates that the curriculum is not merely a theoretical exercise but a responsive framework designed to overcome the human-centric bottlenecks of Data Spaces.

Regarding Learning Formats and Delivery, the empirical data indicate a decisive shift toward educational flexibility and application-oriented learning. The preference for online technical self-training and hands-on practical workshops (each mentioned 13 times) suggests that professionals prioritise the immediate operability of skills. The DIS4SME curriculum reflects this by adopting a challenge-based learning model, where technical standards (e.g., OGC, ISO) are internalised through operational practice rather than passive consumption. This approach effectively bridges the gap between abstract architectural blueprints and the practical implementation of Data Space connectors.

In terms of Certification and Validation, the significant demand for formal recognition—with 58% of participants seeking certificates of attendance or achievement—points toward the emergence of a “competence trust layer.” Similar to the trust frameworks required for secure data exchange, professionals require a standardised validation of their expertise. While micro-credentials represent an emerging trend, the overarching demand for formal validation confirms that a portable skill-attestation system is essential for the European workforce.

By mapping LOs to the stages of the Data Space lifecycle, the proposed framework does more than address knowledge gaps; it establishes a standardised architecture for human interoperability. This alignment ensures that the digital workforce is equipped to navigate the complexity of federated ecosystems, transforming individual expertise into a scalable organisational asset.

5. Discussion

The findings of this study suggest that the transition from isolated data silos to federated Data Spaces represents not only a technical migration but a paradigm shift. While connectors are a necessary technological enabler, the successful implementation of the European Data Strategy ultimately depends on the professional expertise governing them to achieve DSMM Level 3 operational maturity. The empirical evidence presented in this paper supports the existence of a structural Maturity Plateau between DSMM Level 2 and Level 3. Although organisations increasingly succeed in deploying connectors and establishing technical interoperability, they often lack the advanced semantic, legal, and governance competencies required to manage federated data ecosystems. This finding helps explain why many initiatives remain confined to pilot projects rather than evolving into fully operational Data Spaces.

5.1. Beyond the Connector: The Human Factor

From a theoretical perspective, a central finding of this work is that an organisation’s technical readiness, measured by its ability to deploy Data Space components, should not be equated with **organisational readiness**. The human interoperability layer remains a major bottleneck. Our analysis reveals that while basic digital skills are prevalent, specialised competencies in semantic modelling, metadata harmonisation, and legal governance (GDPR/Data Governance Act/Data Act compliance) are critically lacking. Without these skills, the data shared within a Data Space remains dark data: existent but not discoverable, interoperable, or reusable. The empirical basis provided by our survey steering the DIS4SME curriculum ensures that training moves beyond abstract software tools toward process-oriented, challenge-based learning.

5.2. A Roadmap for Human Interoperability

From a practical perspective, our analysis of Data Space maturity indicates that most organisations are currently stalled at DSMM Level 2 (Technical Connectivity). This stagnation, which we define as the Maturity Plateau, is primarily attributed to a structural

deficit in semantic alignment and governance. To bridge this gap, we propose a roadmap for human interoperability structured in three temporal horizons:

- **Short-term (less than one year): Level 2 Consolidation and Technical Integration.** While current training adequately covers traditional BIM/GIS integration (58%), the immediate priority is to standardise these practices using metadata standards like DCAT-AP. This stage ensures that foundational technical pillars (Connectors and Brokers) are robust enough to move organisations out of experimental pilots.
- **Medium-term (1–3 years): Bridging the Plateau through Semantic Mastery.** With 53% of organisations demanding better cross-sectoral integration, the roadmap identifies a shift toward Advanced Semantic Interoperability. Prioritising Learning Outcomes (LOs) in Linked Data and advanced modelling acts as the critical “bridge” to overcome the Maturity Plateau, enabling the automated findability required for complex UDT.
- **Long-term (3–5 years): Level 3 Operational Maturity and Federated Governance.** Addressing the deterrents of unclear governance (37%) and legal complexities, this horizon focuses on Legal and Organisational Competence. Implementing automated governance and federated traceability via micro-credentials (covering the Data Act and GDPR) establishes the trust-based, autonomous environment necessary for DSMM Level 3 operational maturity.

5.3. Impact on European Policy and Sustainability

The implications of this research extend to the goals of the European Green Deal and the Digital Decade 2030. By empowering SMEs to become active “data providers” rather than mere consumers, we foster a more inclusive data economy. The implementation of micro-credentials, as piloted in the DIS4SME project, offers a viable path for the formal recognition of hybrid skills. This roadmap effectively bridges the gap between high-level normative frameworks (EIF, DSSC) and the practical constraints faced by SMEs, ensuring the digital workforce is equipped to meet European sustainability and efficiency targets.

5.4. Limitations and Future Research

This study presents several limitations that should be acknowledged.

First, the empirical component relies on a relatively small sample of 19 experts. Although the respondents represent professionals directly involved in Data Space initiatives, the limited sample size constrains the statistical generalisability of the findings. Future research could extend the analysis through larger quantitative surveys involving a broader set of organisations and sectors.

Second, the analysis focuses primarily on European initiatives such as DSSC. While this follows the current institutional landscape of Data Spaces, additional research is required to assess whether similar competency gaps emerge in other global contexts.

Third, Data Spaces remain an evolving socio-technical paradigm. As architectures, governance models, and regulatory frameworks continue to evolve, the competency framework proposed in this paper should be considered an initial conceptual model that can be refined and validated through further empirical research.

6. Conclusions

The transition toward federated Data Spaces marks a shift where the success of the European Data Strategy ultimately depends on a sophisticated layer of human interoperability. Using the DIS4SME specialised courses as a vehicle for bottom-up analysis, and cross-referencing these findings with a top-down diagnosis of reference architectures, this research highlights that the primary bottleneck for DSMM Level 3 operational maturity is

not technical connectivity, but a “Maturity Plateau” (DSMM Level 2) caused by a shortage of specialised competencies in semantic modelling and legal governance.

This research establishes human interoperability as a formal pillar of Data Space architecture, on par with the technical and legal pillars. It demonstrates that process-oriented training, aligned with the stages of the data lifecycle (Publication, Discovery, Negotiation, Exchange, and Traceability), is the essential driver of increasing SMEs’ organisational readiness. To bridge the identified gaps, the study proposes a roadmap structured across three horizons: Short-term: Consolidation of technical integration (BIM/GIS) and metadata standardization to stabilize Level 2 maturity. Medium-term: Expansion toward advanced semantic interoperability (Linked Data) to overcome the current evolutionary plateau. Long-term: Implementation of federated governance and automated traceability to achieve DSMM Level 3 operational maturity.

By following this path, organisations will be equipped to meet the sustainability and efficiency targets of the European Green Deal. While this study focuses on geospatial data and UDTs, the challenges of human interoperability are common to other strategic sectors, such as Health and Energy.

In this context, the results of this study align with emerging trends in European projects focused on digital skills and capabilities, such as the Skills Data Space, which seeks to federate information on skills, qualifications, and labour market needs. The proposed human interoperability framework can contribute to these initiatives by providing a structured basis for identifying and formalising the skills needed to operate and govern Data Spaces, reinforcing coherence between European data policies and capacity development strategies.

Future research should investigate how these competency requirements align with global data governance models. Furthermore, the role of Artificial Intelligence in automating semantic mapping should be explored as a means to lower entry barriers for smaller enterprises, provided that “Human-in-the-loop” oversight remains central to maintaining trust, data quality, and the core values of the European data ecosystem.

Key Policy and Implementation Takeaways

- Technical infrastructure alone is insufficient to achieve Data Space maturity: the main bottleneck lies in the shortage of specialised competencies in semantic interoperability, governance, and legal compliance.
- The transition from DSMM Level 2 to Level 3 represents a critical Maturity Plateau where organisations must move from technical connectivity toward governed and reusable data flows.
- Targeted training programmes and micro-credentials, such as those developed in DIS4SME, can play a key role in strengthening organisational readiness and enabling SMEs to participate in federated data ecosystems.
- Human interoperability should be recognised as a strategic pillar of Data Space architecture, complementing technical infrastructures and regulatory frameworks.

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Informed Consent Statement: Participation was entirely voluntary, and participants were informed about the purpose of the study before accessing the questionnaire.

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Abbreviations

The following abbreviations are used in this manuscript:

AAS	Asset Administration Shell
AIOTI	Alliance for Internet of Things Innovation
API	Application Programming Interface
BCS	Business Case Scenario
BIM	Building Information modelling
CSV	Comma-Separated Values
DCAT-AP	Data Catalogue Vocabulary—Application Profile
DEP	Digital Europe Programme
DIS4SME	Digital Innovation Skills for Small and Medium Enterprises
DS	Data Space

DSSC	Data Spaces Support Centre
EIF	European Interoperability Framework
EQF	European Qualifications Framework
ETL/ELT	Extract, Transform, Load / Extract, Load, Transform
FAIR	Findable, Accessible, Interoperable, Reusable
GAIA-X	European initiative for data infrastructure
GDAL	Geospatial Data Abstraction Library
GDPR	General Data Protection Regulation
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographic Information Systems
GML	Geography Markup Language
IDSA	International Data Spaces Association
IDS-RAM	International Data Spaces Reference Architecture Model
IFC	Industry Foundation Classes
INSPIRE	Infrastructure for Spatial Information in Europe
IoT	Internet of Things
ISO	International Organisation for Standardization
LOD	Linked Open Data
NGSI-LD	Next Generation Service Interface—Linked Data
OGC	Open Geospatial Consortium
OWL	Web Ontology Language
RDF	Resource Description Framework
SDI	Spatial Data Infrastructure
SHACL	Shapes Constraint Language
SKOS	Simple Knowledge organisation System
SQL	Structured Query Language
WFS	Web Feature Service
WMS	Web Map Service
WPS	Web Processing Service
XML	Extensible Markup Language

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