Research Opportunities and Challenges on Semantic Interoperability

Background

Recognising the fundamental roles of interoperability in building increasingly complex digital solutions, this NESSI[1] paper elaborates how emerging technical trends, i.e., intent-based management, data spaces, and generative AI, may impact **semantic interoperability**, based on the existing efforts around ontology and linked data, and the potential research opportunities and challenges.

Interoperability of software components and systems is fundamental for achieving digitalization benefits, such as increased automation efficiency and better decision-making through improved access to accurate and timely data. For example, system integration in enterprises, linking applications such as ERP, CRM, and supply chain management systems into a coherent platform, relies on the interoperability among previously disparate systems.

European regulations recognize the importance and the benefits of interoperable digital solutions. For example:

- The Interoperable Europe Act aims at strengthening the interoperability of public services across the EU. Interoperability in this context means "the ability of systems to exchange and make use of information. Improved interoperability in the public sector leads to more trust and better communication between public administrations, citizens, and businesses. It requires cooperation around semantic, legal, organizational, and technical issues."[2]
- The European Data Act intends to improve data availability and data sharing within and across sectors. In this context interoperability is defined as "the ability of two or more data spaces or communication networks, systems, products, applications or components to exchange and use data in order to perform their functions."[3] The regulation refers to the standard ISO/IEC 19941:2017[4] which addresses interoperability and portability, particularly relating to cloud services.

The New European Interoperability Framework[5] identified 6 interoperability layers that are important to the development of a European public services ecosystem and the single digital market, i.e., interoperability governance, integrated public service governance, legal interoperability, organizational interoperability, semantic interoperability and technical interoperability. The two lowest layers, i.e., technical and semantic operability, lay the foundation for the upper layers and are most relevant to software and services. Technical interoperability is about how systems and services can communicate with each other to exchange data and information, whereas semantic interoperability ensures that the meaning of the exchanged data and information is preserved and understood throughout exchanges between the parties. In other words, '*what is sent is what is understood*'. Technical interoperability involves standard protocols (HTTP, OAuth) and APIs (REST), common data formats (JSON, XML), middleware platforms (Kafka), etc. On top these technologies, semantic interoperability may be achieved between the data exchanging partners if they share the common context and knowledge about data being communicated, and this is often based on ontologies, metadata, domain-specific standards (e.g. OPC UA), intent abstraction, etc. **This paper is focused on the semantic interoperability layer**, driven by a core research question: *Based on existing standards, platforms and*

[1] NESSI (Networked European Software and Services Initiative), the European association promoting research, development, and innovation in the field of software, data and digital services; http://www.nessi.eu/

[2] https://joinup.ec.europa.eu/interoperable-europe

[3] https://www.europarl.europa.eu/RegData/commissions/itre/lcag/2023/07-14/ITRE_LA(2023)004595_EN.pdf

[4] https://www.iso.org/standard/66639.html

[5] https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf

*regulation for technical interoperability, how can different software systems and services **understand** each other?* The focus is on three levels of semantic interoperability:

- **Infrastructure level**: How can software services and their providers understand the computation, storage and networking resources provided by the infrastructure vendors? Semantic interoperability in this level benefits the integration of resources and services from different vendors and hardware providers, from cloud to edge, into a coherent computing continuum.
- **Data level**: Understanding the meaning of the heterogeneous data from various data providers, and how can AI-based services evaluate the suitability of data for training the AI models? Semantic interoperability at this level facilitate data from different sources and in different natures to be wider understood by different data consumers.
- **Service level**: How different software systems and services can understand each other and autonomously collaborate with each other via the APIs, which is important for the integration of services from different developers into a socio-technical digital ecosystem.

The state of the art of semantic interoperability relies heavily on ontologies and linked data, with syntactic and semantic interoperability of data as a pre-requisite[6]. Operationally, business processes need to be aligned and SLAs with service providers need to be in place to ensure seamless information exchange and workflows. To achieve this a mutual awareness of the knowledge that the involved systems possess is required[7]. Therefore, ontologies and linked data will still be the foundation of semantic interoperability across the levels of infrastructure, data and service.

New trends are emerging from relevant research domains, which brings new opportunities and challenges for semantic interoperability. At the infrastructure level, intent-based networking allows services to configure the networking resources by expressing what level and performance and cost they expected, instead of how to achieve that, and the concept is being generalized to resource management, inspiring attempts such as intent-based computing continuum. At the data level, dataspaces are providing semantic-oriented data sharing environments for many data providers and consumers to understand the data being shared, utilising common data models, ontologies and vocabularies. At the service level, AI, and in particular Generative AI, is providing novel ways to access legacy system APIs, either directly or by generating API invocation code.

This paper will elaborate how these new trends may impact semantic interoperability, based on the existing efforts around ontology and linked data, and the potential research opportunities and challenges. It is worth noting that the three technologies, i.e., intent-based management, data space and generative AI, are not exclusive to the levels of infrastructure, data and software: Intent-based approaches may also help semantic management of software services, and GenAI can also help create the ontologies for data interoperability. Indeed, 100% semantic interoperability is theoretically desirable but practically unattainable. What is achievable is incremental improvements that get closer to the goal by reducing ambiguity and enhancing shared understanding.

Semantic interoperability at infrastructure level: intent-based management

At the infrastructure level, Semantic interoperability is the ability of cloud, edge and network services and their providers to understand each other's interfaces, configuration, forms of authentication and authorization, etc., to exchange information and to use the information that has been exchanged, in order that data and services can seamlessly utilize infrastructure resources from different providers. Portability is

[6] https://en.wikipedia.org/wiki/Semantic_interoperability

[7] Axelsson, J. (2020, July). Achieving System-of-Systems Interoperability Levels Using Linked Data and Ontologies. In INCOSE International Symposium (Vol. 30, No. 1, pp. 651-665).

the capacity to exchange workloads (data and applications) between providers[4,8]. Relocating an application requires adjustments at the information level since each cloud provider has its own information and environmental design. Achieving interoperability and portability is crucial for implementing the computing continuum paradigm, and for developing a more sustainable computing environment[9]. Technical interoperability has been the main focus, providing and standardizing interfaces for observing and controlling resources used by services. The new concept of intent-based resource management, started from Intent-Based Networking (IBN) and rapidly extending to more generic intent-based cloud-edge continuum, aims at achieving semantic interoperability, by allowing infrastructure consumers to understand, and directly request, what they receive from infrastructure providers, in terms of performance, cost, environmental footprint, etc.

Intent-based programming is a new concept that plays a key role in enabling autonomous network operation[10]. It allows network operators to define *what* they want the network to achieve, rather than specifying *how* to achieve it. This high-level approach shifts network management from manual, configuration-heavy tasks to automated, intelligent, self-configurable systems with minimal human intervention. At the core of intent-based networking (IBN) is the ability to translate business or operational intents into low-level network policies and configurations. Since intent-based models are typically expressed in platform-agnostic formats (such as APIs or declarative languages), they abstract away the underlying vendor-specific implementations and complexities. This abstraction enables diverse systems — developed by different vendors or using different architectures — to interoperate more effectively, as they are interacting through common, understandable intents rather than incompatible low-level protocols.

IBN presents a promising shift in network management, but it still faces research challenges that need to be addressed for broader adoption and effectiveness. Key challenges include: accurately converting high-level; ambiguous human intents into low-level network configurations; ensuring that the translated network behaviour truly reflects the user's intent; developing open, extensible intent languages and APIs for ensuring interoperability across diverse platforms.

Intent-based management is also inspiring innovation in the cloud-edge computing continuum, lifting interoperability between resource services and their providers into semantic level. By allowing resource users to specify, at a high abstraction level, their expectations on the various aspects such as performance, cost, environmental footprint, intent-based continuum enable the resource consumers to understand what services they receive from the resource providers. Such semantic interoperability is built on top of the significant effort that has been made to improve interoperability in the cloud-edge-IoT continuum, including a taxonomy of the computing continuum reference blocks, with the specification of reference architectures based on ISO/IEC/IEEE 42010:2022[11], the integration with domain-specific standards such as RAMI or SGAM, or the integration with Digital Twins architectures[12]. Despite the effort invested, interoperability is still a key

[8] Stravoskoufos, K.; Preventis, A.; Sotiriadis, S.; Petrakis, E.G. A Survey on Approaches for Interoperability and Portability of Cloud Computing Services. In Proceedings of the 4th International Conference on Cloud Computing and Services Science (CLOSER 2014), Barcelona, Spain, 3–5 April 2014, 112–117.

[9] Ramalingam, C., & Mohan, P. Addressing semantics standards for cloud portability and interoperability in multi cloud environment. Symmetry, 13(2), 317, 2021.

[10] https://www.tmforum.org/autonomous-networks-project/

[11] https://www.iso.org/standard/74393.html

[12] https://eucloudedgeiot.eu/wp-content/uploads/2023/07/D4.3-Toward-an-European-ecosystem-for-the-computing-continuum-Working_v1.1.pdf

challenge and barrier to achieve full coverage, easy management and portability, and wide data sharing[13,14,15]. To have a full computing continuum, new technologies are required to enable better integration of cloud services and, thus, better coverage. Cloud providers should be able to integrate their infrastructure to increase the areas covered whilst reducing total investment and increasing the sustainability of the infrastructure, as telecommunications providers have been doing during the last few years. However, this raises interoperability issues which are still open.

- **Sharing computing resources.** In the computing continuum, computing resources are typically distributed at locations close to the end users, not only in big data centres. This may favour the proliferation of small local data centres, supporting specific areas. New techniques are required to allow and promote seamless and trustworthy interactions and resource sharing between cloud providers, to enable data and application portability depending on developers' and users' intents, without them having to specify where the resources are provided. Artificial Intelligence, Heuristics and evolutionary algorithms can be used to improve the resource selection and sharing, to balance energy consumption, latency, or optimizing resource allocation.
- **Computing continuum observability.** If computing resources are shared between different providers, observations and monitoring data should also be shared between them so that they can manage resource usage and the distribution of different applications to assure Quality of Service. This data should be shared such that it is understandable by the different providers, despite the heterogeneity between providers.

For shared resources, each provider should be able to manage the different computing nodes and how applications are distributed to achieve the desired quality of service and to reduce energy consumption and cost. The computing continuum should be able to automatically move services efficiently between different computing resources belonging to the same service provider or different providers depending on the loads on the different resources and the status of the applications. Service providers should support automatic or semi-automatic application portability, following the consumers' intents instead of concrete instructions on how to allocate resources and move services among them.

- **Resource description.** Resources should be described in a standardized and detailed way so that applications can understand their characteristics and capabilities. **Cross-cloud provider compatibility.** Currently, cloud providers offer different development frameworks which tie an application to a provider. Applications should be designed in such a way that they can run smoothly on different platforms and cloud environments, avoiding dependency on vendor-specific features.
- **Management.** Service providers should be able to adapt and reconfigure some characteristics of the computing nodes to obtain a better quality of service, reduce the cost, improve sustainability, etc. Operators usually lack the appropriate languages, tools, and mechanisms to configure, plan, prepare, and execute tasks in heterogeneous computational environments.
- **Access Control.** Applications must have adequate access to resources without compromising security. New techniques are required to implement Identity management, authorization, and confidentiality in multi-cloud computing environments.

[13] Lee, C. A., Bohn, R., & Michel, M. (2022, December). The IEEE 2302–2021 Standard on Intercloud Interoperability and Federation: Seamless Cloud-agnostic Interoperability Management for Resource Discovery, Access and Trust. In 2022 Cloud Continuum (pp. 1-9). IEEE.

[14] Bachoumis, A., Andriopoulos, N., Plakas, K., Magklaras, A., Alefragis, P., Goulas, G., ... & Papalexopoulos, A. (2021). Cloud-edge interoperability for demand response-enabled fast frequency response service provision. IEEE Transactions on Cloud Computing, 10(1), 123-133..

[15] Korontanis, I., Tserpes, K., Pateraki, M., Blasi, L., Violos, J., Diego, F., ... & Dazzi, P. (2020, June). Inter-operability and orchestration in heterogeneous cloud/edge resources: The accordion vision. In Proceedings of the 1st Workshop on Flexible Resource and Application Management on the Edge (pp. 9-14).

In summary, the effort of increasing the coverage of infrastructure, from central cloud to local datacentres and edge resources, is leading to challenges on the efficient management and utilization of the scattered and heterogeneous resources. Intent-based management allows resource consumers to express **what** they expect from the infrastructure instead of **how** to manage the resources offered by different providers to achieve the expectation and therefore provides a solution towards semantic interoperability between different resource providers. The research challenge is how to allow different stakeholders to express, manage and observe the intents, how to enable different resource managers to understand the meaning of the intents, and how to bridge the gap between high-level and abstract intents and the concrete resource allocation and adaptation actions. Knowledge representation techniques are gaining attention on addressing the challenge of intent expression and exchanging, based on the TM Forum's effort on using knowledge graph to define intent[16]. To bridge the gap between intent and management actions, advanced AI techniques, such Natural Language Processing, continual learning, federated and decentralized intelligence, will play an important role, and eventually aiming at a cognitive computing continuum that can understand what the resource consumer's intents, automatically adapt the resources to fulfil the intents by continuously observing and adjusting the resource usage, and collaborate with each other to achieve higher level objectives, as is investigated by a number of ongoing Horizon Europe projects on cognitive continuum[17][18].

Semantic interoperability at data level: Data Spaces

Semantic interoperability of data involves how the data providers and data consumers can understand the data which is shared between them. In practical usage, data interoperability issues may emerge from various data usage scenarios, such as integrating digital twins, building data pipelines across organizations, providing data to AI training, fine-tuning or inference, etc. The building of data spaces has one of its main objectives towards facilitate semantic interoperability between the participants of data spaces. In this section, digital twin integration is used as a sample scenario to discuss the importance and challenges on data-level semantic interoperability, and how data space technologies may help solve this problem.

A Data Space is a framework that supports data sharing within a data ecosystem. It provides a clear structure for participants to share, trade, and collaborate on data assets in a way that is compliant with relevant laws and regulations and ensures fair treatment for all involved[19]. The semantics of data is a key focus in the building of data spaces, which provides a promising way towards enhancing the semantic interoperability of data, through common frameworks and standards that ensure data exchanged between different organizations carries consistent meaning. They promote the use of shared ontologies, reference data models, and vocabularies that enable machines and humans to interpret data uniformly, regardless of its origin, and encourage collaboration among stakeholders to co-develop and maintain these semantic assets along the lifecycle of data sharing. As an ongoing work, the following directions are gaining attention among the data space community towards semantic data interoperability.

- **The semantic asset in the data spaces.** Semantic metadata, such as common vocabulary of data being shared and semantic annotations of datasets are proposed to be a standard layer of the data spaces, providing references for different stakeholders to set up a common understand of the data semantics[20].

[16] https://www.tmforum.org/toolkits/intent/
[17] INTEND: Intent-based data operation in the computing continuum. https://cordis.europa.eu/project/id/101135576
[18] ENACT: Adaptive Scheduling and Deployments of Data Intensive Workloads on Energy Efficient Edge to Cloud Continuum. https://cordis.europa.eu/project/id/101135423
[19] https://language-data-space.ec.europa.eu/help/faq/what-data-space_en
[20] Robert David, Petar Ivanov, Vladimir Alexiev, Raising the Role of Vocabulary Hubs for Semantic Data Interoperability in Dataspaces. https://semantic.internationaldataspaces.org/wp-content/uploads/2024/10/presentation.pdf

- **Standardization efforts.** A set of standardization requests are handling the semantic interoperability, such as the maturity model for common European data spaces, the trusted ontologies and data models, the data catalogues, the trusted data transaction, etc[21].
- **Semantic integration functionality**. Several functions are considered to play an important role in maintaining semantic assets and facilitating the semantic interoperability among stakeholders, such as the vocabulary hub for domain-specific vocabularies, the metadata broker for the registration and maintenance of self-description of data semantics. These have been included into the system layer of the reference architecture of internation data spaces[22].
- **Semantic metadata and integration beyond ontologies**. Ontologies, as a key solution in data spaces to provide shared vocabularies, are increasingly criticized for being heavy, costly to develop and maintain, and sometimes too rigid in rapidly evolving domains. Large Language Models (LLMs) are emerging as a potential complementary or alternative approach, offering flexible, context-aware semantic mapping without requiring strict formalization, leveraging the universal knowledges embedded in the trained models, in a more implicit, approximate and non-symbolic way. The challenge is the explainability, consistency, and trust of using such embedded knowledge in easing data interoperability.

In summary, while data spaces are introducing standards to support semantic transparency in data sharing, ensuring that stakeholders consistently and correctly interpret this data remains a central challenge, pointing to the unresolved issue of semantic interoperability at the software and service level.

Semantic interoperability at the software and service level: Generative AI for service integration

At the software and service level, effort on technical interoperability has been concentrated around APIs, with API description standards like OpenAPI, API design tools like swagger, API Gateways, etc. With the widely accepted API standards and tools, software services can easily communicate with each other, despite their difference on software and infrastructure stacks. However, it is not guaranteed that they understand what they have communicated. To achieve such semantic interoperability, the classical solution is to build ontologies that capture the common knowledge needed for both sides to understand each other. However, building the effective ontology itself is a heavy work. Generative AI, or GenAI, provides a new and promising approach to the semantic interoperability between software services, based on its embedded common-sense knowledge of the world, its capability of interpreting and generating both natural language contents and programming language code. The following are identified as emerging practices using GenAI for semantic interoperability and elaborate the relevant research opportunities and challenges.

- **GenAI to facilitate system integration projects**. Generative AI is widely used in software engineering[23] and has the value to facilitate software and system integration projects from different perspectives, but the current focus is heavily on generating code to reduce human effort. More research is needed to explore how GenAI can play solid roles in the entire software development and system integration projects, e.g., helping understand customer requirements, analyzing and explaining system APIs, generating code snippets to bring communication gaps between systems, generating test cases to evaluate the integration results, etc.

[21] Coen Janssen, Sematnic inteoperability in Data Spaces, https://semantic.internationaldataspaces.org/wp-content/uploads/2024/09/Semantic-Interoperability-in-Data-Spaces-1-Oct-2024-Coen-JANSSEN-EC.pdf
[22] https://docs.internationaldataspaces.org/ids-knowledgebase/ids-ram-4/layers-of-the-reference-architecture-model/3-layers-of-the-reference-architecture-model
[23] Ebert, C. and Louridas, P., 2023. Generative AI for software practitioners. IEEE Software, 40(4), pp.30-38.

- **GenAI agents as the connector between legacy software systems**. Intelligent agents powered by GenAI can interact with legacy software systems through their APIs, which are registered as tools[24] or context[25] for the GenAI agents. These agents use the APIs to obtain external data or manipulate external systems, as part of their task for content generation or decision making. During the process they can interpret data formats, orchestrate data flows, and handle protocol translations on demand. In this way, GenAI agents acts as the integrator of the legacy systems, saving the heavy coding effort for tradition system integration. A recent standard of Model Context Protocol (MCP)[26] provides a way to wrap up and register any external and legacy software systems as tools to LLM agents. It is adopted by mainstream LLM providers such as OpenAI and Anthropic. With promising results from experimental projects, the challenge for large-scale application relies on how to solve the reliability and cost of intelligent agents in interacting with legacy systems. A primary driver of this transition is the 'AI for Interoperability' (AI4OP) initiative[27]. Led by SEMIC, this initiative explores the synergy between AI and semantics to bridge data silos and foster innovation across public organisations.
- **GenAI for Semantic Data Interoperability.** GenAI can be used to understand the context and meaning behind diverse datasets, effectively acting as a translator between disparate data models. This can be done either relying on the knowledge embedded in the GenAI models, or with the help of external knowledge in terms of documents and ontologies. This semantic layer helps teams maintain data quality, reduce misunderstanding, and simplifiy data exchange across different platforms. A major challenge here is to provide the right knowledge to the GenAI models or agents, which is sufficient for them to understand the data while not overwhelming them with too much information that cause the loss of focus and increase the cost. The research and practice on Retrieval Augmented Generation (RAG) is expected to provide methods and technologies for this direction.
- **Interoperability of GenAI Agents.** As more organizations adopt multiple AI systems, the challenge shifts to having these AI agents communicate coherently among themselves. Standardizing protocols and data formats for AI-to-AI interaction becomes crucial for maintaining reliable workflows. In this way, GenAI agents can function in tandem—interoperating seamlessly to automate complex processes and deliver next-level insights to end-users.

In summary, GenAI is a new and fast-developing technology, and the use of it for software integration and interoperability is still not widely investigated. Challenges exist on how to handle the indeterministic nature of GenAI models, the lack of standards for describing external APIs and data, the concern on security and privacy of using GenAI services. Large-scale demonstrators or proof-of-concept prototypes will significantly boost the research and innovation in this direction.

Recommendations and Conclusion

Software and system interoperability is still an important problem that needs to be addressed to increase the competitiveness of solutions and obtain the benefits of digitalization. From the research point of view, a main challenge is sematic interoperability, i.e., how the different components understand each other. New technologies, such as intent-based management, data spaces, and generative AI, bring opportunities for innovative solution at the levels of infrastructure, data, and software. This leads to the following recommendation from NESSI.

- Intent-based management should be extended from networking to the entire infrastructure built on the Cloud-Edge-IoT computing continuum, exploring more human-friendly ways of expressing intents, including the use the natural language. This will enable cross-vendor compatibility which,

[24] https://platform.openai.com/docs/guides/function-calling
[25] https://www.anthropic.com/news/model-context-protocol
[26] https://github.com/modelcontextprotocol
[27] https://interoperable-europe.ec.europa.eu/collection/semic-support-centre/ai-interoperability

combined with new frameworks and tools, will allow developers to create applications that can run on different platforms and seamless roam among different cloud environments.

- Attention is needed for the standards, methods and tools with data spaces to facilitate the maintenance and usage of semantic metadata, and the link of metadata between different datasets, with exploration of using LLMs as complementary to classical metadata based on ontologies. This will ease the fuse of data from different devices, sensors, and providers in building valuable data applications.
- New methods, tools and platforms are needed to facilitate the systematic usage of generative AI in supporting software-level interoperability, by using AI to support integration projects, generate glue code between components, and directly as media components between different systems.
- Reliability, trustworthiness and explainability are important properties for semantic interoperability of infrastructure, data and software, especially when the use of AI and generative AI introduces implicit meta data, emerging behaviours, and uncertainty.

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