

Supplementary Material

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1 Interoperability: historical background and evolution

Interoperability, as discussed in main body of this manuscript, is a multifaceted concept with definitions that vary based on the context and the perspectives of the authors [1]. For instance, it is often described [2, 3, 4] as

the ability of two or more systems or components to exchange information and to use the information that has been exchanged.

Alternatively, it is also defined [5, 6] as

the ability of systems, organisations, or units to work together by exchanging information and services to enable them to operate effectively.

In the enterprise context, interoperability refers not only to the ability of systems to exchange information but also to the capacity of enterprises to interact across multiple levels, such as processes, services, and data management systems [6]. Achieving successful collaboration between systems requires the integration of technical, organisational, and semantic layers, as well as the resolution of interoperability barriers—such as organisational structure and legal concerns [6, 3].

Interoperability extends beyond technical exchanges to include the semantic understanding and effective use of the shared information [1]. This has become critical for enabling global collaboration across industries, ensuring systems can work together seamlessly despite differing technical frameworks and organisational structures [3]. In distributed simulation systems, for example, it is necessary not only to exchange data but also to align conceptual models so that the information exchanged is understood and utilised effectively by all systems involved [7].

While initially focused on technical challenges, the concept of interoperability has evolved to encompass a broader range of socio-technical, organisational, and legal concerns. In its modern form, interoperability is crucial for cross-domain collaboration, enhancing productivity and fostering innovation across diverse industries [3]. The INTEROP Project underscores that interoperability involves more than the technical exchange of data and includes the capacity to use that information meaningfully, ensuring both semantic understanding and trust in the validity and content of shared information [3]. This reflects the increasing complexity of interoperability, as it now spans technical, organisational, and legal domains [6].

1.1 Early interoperability: addressing communication gaps (1960s–1990s)

The concept of interoperability first emerged in the military domain, driven by communication failures between different branches of the U.S. Department of Defense (DoD) [8]. In the 1960s, critical events like incompatible radio systems highlighted the need for systems to communicate effectively. This led to the publication of DoD Directive 4630.5 in 1967, which sought to standardise military communications across different forces [1].

Key Developments:

- *1977*: The DoD issued updated directives to improve technical and operational interoperability, marking the first formal efforts to address system incompatibilities. However, these early efforts remained largely technical, focusing primarily on communication systems [8].
- *1980s-1990s*: The scope of interoperability expanded beyond technical issues, addressing larger operational and command challenges in real-world scenarios such as the Persian Gulf War. The military context served as a proving ground for evolving frameworks like the Levels of Information Systems Interoperability (LISI), developed by MITRE [9, 7]. This framework classified system maturity into five levels, ranging from isolated systems to fully integrated, interoperable enterprises.

During this period, simulation systems played a crucial role in advancing interoperability, particularly in military exercises. Projects like SIMNET demonstrated the potential of integrating simulation systems from different branches in a shared virtual environment [7]. This laid the groundwork for the development of standards such as Distributed Interactive Simulation which standardised messages between simulation entities to facilitate coordinated exercises [1].

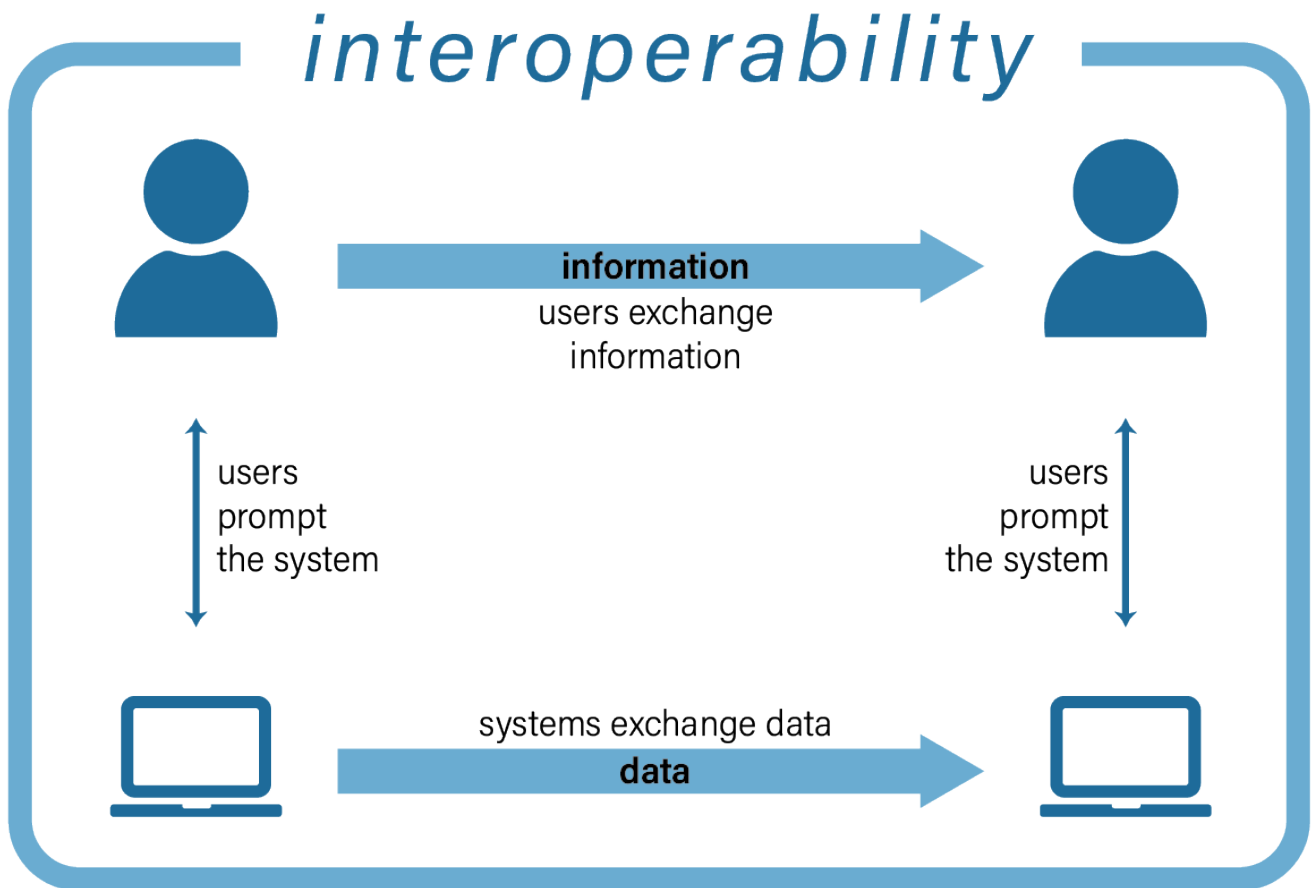


Figure 1: **Interoperability framework: user-system interactions for data and information exchange.** This figure demonstrates the concept of interoperability in information systems, emphasising the bidirectional flow of communication between users and systems, as well as between different systems. Users prompt the system through interactions, which in turn provides outputs based on user requests. Users can also exchange information with other users, enabling collaboration and knowledge sharing. Simultaneously, systems exchange data autonomously, ensuring smooth operation and integration between different platforms. This figure highlights the dual layers of interoperability: human-to-human and system-to-system exchanges, which are essential for efficient and cohesive operation in complex data environments.

1.2 Transition to broader applications: organisational and technical models (1990s–2000s)

As systems grew more complex, interoperability frameworks evolved to address not only technical concerns but also organisational and process-oriented challenges. The focus shifted from mere technical compatibility to ensuring that systems could cooperate at strategic, operational, and organisational levels [1].

Key developments:

- **Organisational Interoperability Maturity Model (OIM):** Developed by the Australian Defense Science and Technology Organisation in 1999 [8], OIM extended the concept of interoperability beyond technical concerns to include organisational collaboration. It emphasised the importance of not only sharing data but also aligning goals, command styles, and processes across systems. The model highlighted the need to align organisational structures, management processes, and business rules alongside achieving technical integration.
- **Standards integration:** As interoperability became critical across multiple domains, standards such as ISO 14258 (Concepts and Rules for Enterprise Models) and ISO 15704 (Requirements for Enterprise-Reference Architectures) were introduced [3]. These standards provided structured approaches for enterprises to model, align, and integrate systems at both technical and organisational levels, offering a framework for achieving interoperability through enterprise modelling.

Streamlining of technical and organisational models Both LISI and OIM, though impactful, faced challenges in adoption outside military contexts. Their complexity highlighted the need for user-friendly, adaptable frameworks that can apply to broader industries, not only for technical exchanges but also for organisational integration. As systems become more sophisticated, standards such as ISO play a critical role in fostering interoperability in complex domains [1].

1.3 Interoperability in Complex Systems: modern technological integration (2000s–Present)

With the rise of Cyber-Physical Systems (CPS), Industry 4.0, and the Internet of Things (IoT), the concept of interoperability has evolved to address more multi-domain and interdisciplinary challenges [10]. These modern systems require not only real-time data exchange but also integration across technical, organisational, and regulatory boundaries [1].

Key developments:

- **Cyber-Physical Systems (CPS):** CPS represent the intersection of physical processes and computational control, introducing new challenges for interoperability. These systems require real-time data exchange between embedded computers and physical devices, leading to new interdisciplinary integration issues.
- **Composability and conceptual interoperability:** achieving interoperability in complex systems requires more than technical integration. The concept of composability emphasises aligning conceptual models across systems, ensuring that data is exchanged, interpreted, and used consistently. This is especially important in distributed simulation systems [7].
- **Tool interoperability and integration:** CPS development requires different engineering tools to collaborate seamlessly. However, tool integration has lagged due to a lack of standardised models. Visual analytics has been proposed as a solution to help engineers visualise and bridge gaps in tool integration, leveraging frameworks like LISI to support tool chain interoperability in CPS systems [3].
- **Enterprise interoperability frameworks:** frameworks such as the European Interoperability Framework (EIF) and the ATHENA Interoperability Framework address issues like data integration, process synchronisation, and cross-domain collaboration [6]. These frameworks provide structured approaches to overcoming interoperability barriers in complex systems.
- **Expanding definitions and types:** in modern systems, interoperability spans beyond technical systems to socio-technical and organisational integration. The INTEROP Project categorises these types into technological, socio-technical, and crosscutting dimensions, ensuring semantic understanding across different platforms [3]. A tertiary study identified over 36 types of interoperability, including organisational, legal, and cultural aspects, which are increasingly crucial in multi-domain systems like smart cities and global industrial networks [11]. For a visual overview, refer to Figure 2.
- **Interoperability barriers:** barriers hindering interoperability are categorised into conceptual (semantic/syntactic differences), technological (incompatible IT standards), and organisational (differences in structure and legal frameworks).

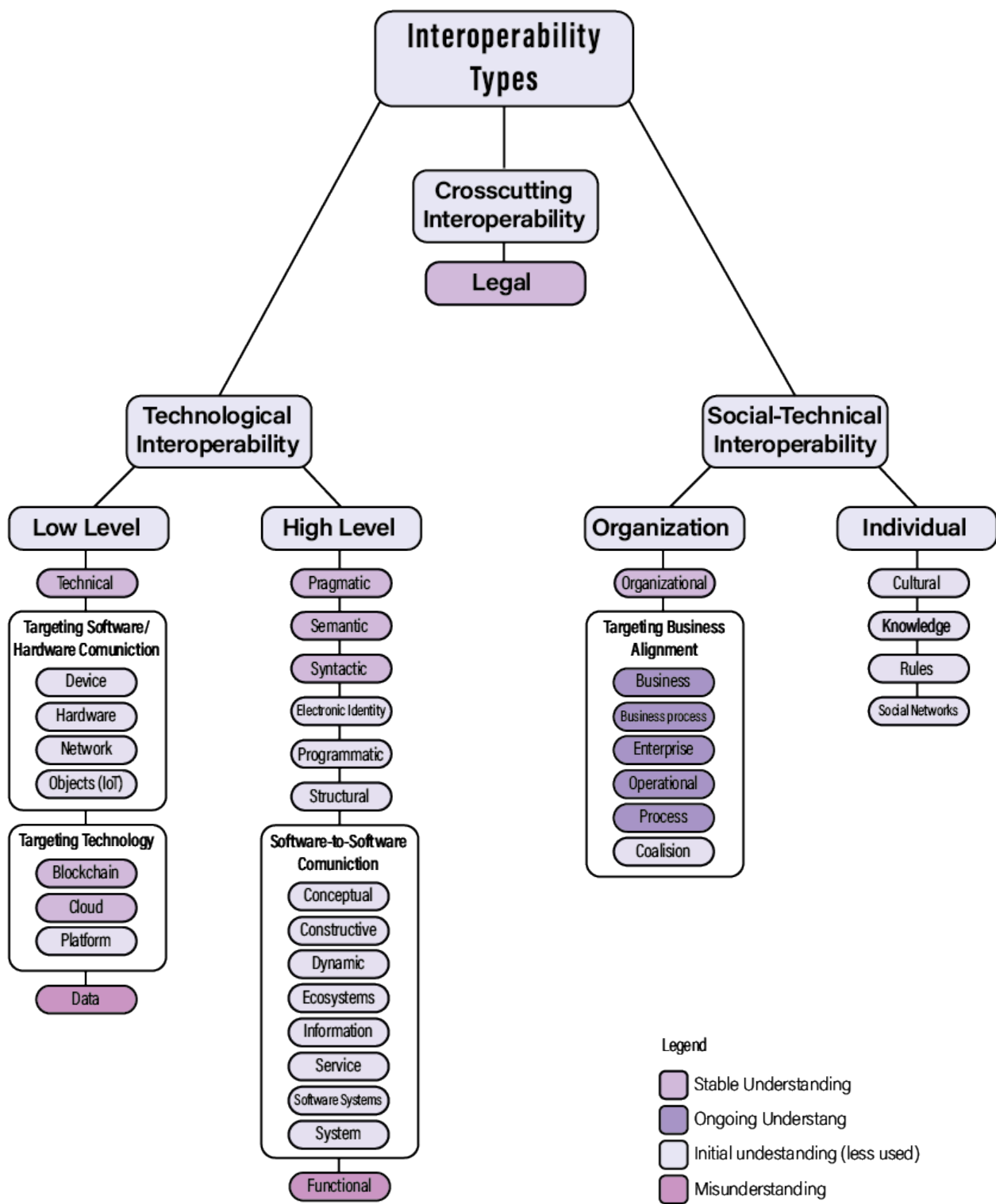


Figure 2: (Caption on next page.)

Figure 2: **Classification of interoperability types.** This figure illustrates a comprehensive taxonomy of interoperability types, dividing them into:

- *technological interoperability*, further categorised into:
 - low level: focusing on technical communication between devices, hardware, and networks, including emerging technologies like IoT, blockchain, cloud, and platforms;
 - high level: addressing more abstract communication, such as semantic, syntactic, and structural aspects, emphasising software-to-software interactions and system-level integration;
- *social-technical interoperability*, categorised by:
 - organisation: targeting business alignment through operational, enterprise, and process-level collaboration;
 - individual: focusing on human factors like cultural knowledge, social networks, and adherence to rules;
- *crosscutting interoperability* includes legal aspects that span both technological and social-technical fields, ensuring compliance and coordination.

The legend below outlines four levels of understanding: stable, ongoing, initial, and areas of potential misunderstanding. This hierarchical model highlights how multiple layers of interoperability are essential for aligning technological systems with organisational goals and individual interactions. Adapted from [11].

1.4 Towards a unified interoperability framework: emerging technologies and future directions

As Industry 4.0, IoT, and blockchain technologies become more prevalent, the demand for advanced interoperability solutions continues to rise. Traditional models like LISI are being adapted and extended to meet the needs of heterogeneous, decentralised, and dynamic systems. Interoperability now encompasses not just technical exchanges but also the ability to adapt to new operational environments and collaborate across organisational and jurisdictional boundaries [1].

Blockchain as an enabler of interoperability: blockchain has emerged as a key technology in enabling secure, transparent, and trust-based interactions between systems. Blockchain interoperability allows information to be shared consistently across platforms while maintaining data integrity and security [3].

Key developments:

- Levels of Conceptual Interoperability Model: it defines six layers of interoperability, ranging from technical and syntactic layers to dynamic and conceptual layers, providing a comprehensive framework for understanding interoperability across multiple levels [8, 10].
- Interoperability Assessment Models: these models have evolved to assess an organisation's readiness for interoperability, focusing on potentiality, compatibility, and performance through both qualitative and quantitative measures [6].
- Mathematical methods and real-time systems: researchers are exploring mathematical models to quantify interoperability in real-time, particularly in self-forming networks and adaptive systems.
- Tool integration in CPS: the challenge of integrating tools across disciplines in CPS development remains significant. Future efforts will likely focus on improving tool chain interoperability through visual analytics and data-driven models that can manage the heterogeneous nature of engineering tools [3].
- Future research directions: the development of scalable, cost-effective interoperability solutions that integrate performance, cost, and sustainability is essential for industries like healthcare, defence, and smart cities [6].

2 Case studies in Interoperability

This section will provide detailed case studies from various industries where interoperability challenges and solutions have been applied [1].

2.1 Telecommunications and logistics

In industries such as telecommunications and logistics, interoperability assessments have proven valuable in streamlining communication between systems [6]. These industries rely on federated interoperability models, which allow

127 systems to manage dynamic interactions without predefined structures. This flexibility ensures that operations can
128 scale and adapt in real-time. In addition to technical challenges, business collaborations in these industries often
129 face human-related interoperability issues, where aligning organisational goals and strategies is as critical as technical
130 alignment [3].

131 **2.2 Healthcare systems**

132 **Transition to patient-driven interoperability and Blockchain-enabled EHR integration** Traditionally,
133 healthcare interoperability has been institution-driven, with hospitals, clinics, and pharmacies exchanging clinical
134 data through centralised systems or Health Information Exchanges (HIEs) [12]. However, recent efforts have shifted
135 toward patient-driven interoperability, enabling patients to control their health data [13]. Legislation such as the 21st
136 Century Cures Act and the HITECH Act promotes patient access to health records via standardised Application
137 Program Interfaces.

138 In this context, blockchain technology has emerged as a potential enabler, providing digital access rules, data
139 aggregation, and smart contracts to securely manage and share health data [13, 14]. Blockchain decentralises data
140 control and allows real-time verification of clinical transactions, reducing costs associated with patient matching, data
141 authentication, and regulatory compliance [14]. Although blockchain has the potential to improve Electronic Health
142 Record (EHR) interoperability by enhancing security, reliability, and data integrity, challenges remain, such as data
143 scalability, privacy concerns, and the lack of standardisation across platforms [14].

144 **Cross-Enterprise Document Sharing (XDS)** The Integrating the Healthcare Enterprise (IHE) Cross-Enterprise
145 Document Sharing (XDS) initiative provides a mechanism for sharing healthcare documents between multiple providers.
146 XDS uses standardised document metadata and ebXML registries to securely share medical summaries and health
147 records across institutions, facilitating both episodic and collaborative care [15].

148 **Blockchain for patient care and data management** Blockchain technology also addresses challenges in man-
149 aging EHRs, HIEs, and Remote Patient Monitoring systems [16, 12]. For example, initiatives like Embleema and
150 the Synaptic Health Alliance use blockchain to facilitate secure, decentralised data management between healthcare
151 stakeholders, enabling real-time monitoring, telemedicine, and cross-platform applications such as Personal Health
152 Records [16].

153 **eHealth: addressing multi-layer interoperability challenges** The RIDE Project (Roadmap for Interoperabil-
154 ity of eHealth Systems) identified multiple layers of interoperability issues, including syntactic and semantic inter-
155 operability within EHR systems [15]. Incompatible messaging standards and mismatched patient identifiers across
156 organisations were key challenges. To address these, Health Level 7 (HL7) protocols, particularly Version 3, have been
157 recommended for their ability to standardise and improve interoperability in patient records [15].

158 **Federated Health Information Systems (HIS)** An example of interoperability in federated healthcare networks
159 is the OpenInFSE Project in Italy, which developed a federated interoperability architecture for Health Information
160 Systems (HIS) across regional networks [17]. Using a Service-Oriented Architecture with Web Services technology,
161 the project enables real-time sharing and access to EHRs and clinical documents across various hospitals [17]. The
162 system also implemented a push-based event notification feature, reducing the time required for healthcare providers
163 to access critical information, thereby streamlining patient care [17].

164 **Federated Research Infrastructure: The JA-InfAct Project** The JA-InfAct Project developed a federated
165 research infrastructure for health information systems across multiple countries in the European Union [18]. The
166 project aimed to support population health and health system performance assessment by sharing aggregated, real-
167 world healthcare data while maintaining compliance with GDPR. Process mining techniques were applied to analyse
168 care pathways, such as those for acute ischemic stroke patients, allowing each region to conduct local analyses and
169 share only aggregated results via a Coordination Hub [18]. This method avoided the transfer of personal data while
170 facilitating international comparisons [18].

171 **Federated Data Warehouse for Healthcare Interoperability** The Austrian healthcare system implemented a
172 Federated Data Warehouse model to improve national and international interoperability among healthcare providers
173 and social insurance institutions [19]. This approach virtually integrates data repositories from different institutions
174 without centralising the data physically. The system allows healthcare providers to query and retrieve patient infor-
175 mation across regions, facilitating faster access to critical data and improving patient care.

176 The Data Warehouse follows the MAGDA-LENA framework for exchanging patient-related data, using standard-
177 ised formats like HL7 and ensuring security through encryption and role-based access controls [19]. This architecture
178 supports various services, including e-prescriptions and the development of lifetime health records, offering a scalable
179 solution for managing healthcare data across multiple regions.

2.3 Finance

Blockchain in cross-chain operations: cryptocurrency and asset transfer A significant case study in blockchain interoperability involves the cross-chain transfer of assets between different blockchain platforms. For example, the integration of sidechains enables the transfer of assets from a main blockchain to a sidechain (an independent blockchain) without modifying the main blockchain. One notable example is RootStock, a smart contract platform that allows for two-way asset transfers between Bitcoin [20] and Ethereum. This system employs federated two-way pegs, which ensure secure transfer by locking and unlocking tokens between two blockchain systems [21].

These systems also rely on Hashed Time Lock Contracts to ensure atomicity, meaning the entire transaction must either be completed successfully or fail. This approach is widely utilised in atomic swaps, where users exchange different cryptocurrencies across blockchains without needing a trusted third party. Solutions like XCLAIM and BTCRelay are vital for cryptocurrency exchanges, enabling secure asset trades across platforms and bridging Bitcoin and Ethereum [21].

2.4 Real-world costs of poor Interoperability

Poor interoperability can have significant economic impacts. For example, inadequate interoperability in the U.S. Capital Facilities Industry in 2004 resulted in \$15.8 billion in costs, while healthcare systems in the U.S. waste approximately \$30 billion annually due to interoperability issues [6].

3 Industry-specific challenges in Interoperability

Interoperability challenges vary significantly across manufacturing, healthcare, and public administration industries. These sectors face unique barriers due to differences in technological infrastructure, data standards, and regulatory requirements [6, 3]. Tailored interoperability solutions are essential for overcoming these challenges [1].

3.1 Manufacturing

Manufacturers face challenges in integrating legacy systems with modern IoT-based platforms, ensuring real-time communication across the supply chain [6].

3.2 Healthcare

Interoperability in the healthcare sector is particularly challenging due to the sheer volume of clinical data generated and strict data privacy regulations [3, 13]. Addressing semantic and legal interoperability could save approximately €99 billion in the European Union alone [6].

Data Volume, Privacy, and Security The growing volume of clinical data, such as the vast datasets generated by cardiac MRI scans, complicates data sharing and storage. Blockchain technology has been proposed as a solution, though current systems cannot handle large data sets on-chain. Instead, off-chain data storage is used, with blockchain managing permissions and metadata [13].

Privacy and security concerns are critical in healthcare. Blockchain’s pseudonymous structure could expose patient data to risks if public keys are linked to identities, conflicting with regulations like the General Data Protection Regulation (GDPR), which includes the “right to erasure” clause that contradicts blockchain’s immutability. To address this, permissioned blockchains and selective disclosure technologies are being explored to ensure compliance with privacy laws [13].

Challenges in patient engagement and EHR interoperability A significant barrier to blockchain-enabled patient-driven interoperability is patient engagement. Moving from institution-centric models to patient-driven ones requires patients to manage their digital health data, including public keys and permissions, necessitating patient-friendly tools like apps [13]. Furthermore, incentivising healthcare institutions to adopt patient-driven interoperability without immediate financial benefits remains a challenge [13].

The integration of blockchain technology with Electronic Health Record (EHR) systems also faces several challenges:

- *Lack of standardisation:* Variations in data standards across healthcare systems result in inconsistent data formats, making data sharing difficult [14].
- *Data security and privacy:* While blockchain improves security, it introduces privacy vulnerabilities, especially regarding compliance with regulations like Health Insurance Portability and Accountability Act and GDPR [14].
- *Scalability and high data volumes:* The large amounts of data generated, particularly from imaging and diagnostics, pose challenges for data storage and processing on blockchain platforms [14].

228 **eHealth: Technical Barriers and Data Standards** In healthcare, the lack of standardised data exchange formats
229 and patient identifier systems is a significant barrier to interoperability [15]. Different healthcare organisations often
230 use proprietary formats for messaging interfaces and patient identification systems, complicating efforts to establish
231 interoperable systems. For example, matching patient IDs across hospitals requires a system like a Master Patient
232 Index [15].

- 233 • *Syntactic Interoperability* ensures that healthcare messages are exchanged correctly using standards like SOAP
234 or ebXML.
- 235 • *Semantic Interoperability* ensures that shared data is consistently understood, requiring shared vocabularies such
236 as SNOMED CT or LOINC [15].

237 **EHR and semantic interoperability challenges** Achieving interoperability in Electronic Health Records (EHRs)
238 remains a challenge due to issues with semantic mediation, where EHR data must be converted between different
239 formats [15]. Standards like CEN EN 13606, HL7 Clinical Document Architecture, and openEHR aim to provide
240 structured, machine-readable data, but true semantic interoperability across heterogeneous systems is still difficult.
241 Systems like IHE XDS support secure discovery and sharing of medical records but ensuring content interoperability
242 and standardising clinical document formats, such as Clinical Document Architecture Level 2 and 3, remains a challenge
243 [15].

244 **Federated Health Information systems and challenges** Federated architectures, such as Italy’s OpenInFSE
245 Project, face several industry-specific challenges [17]:

- 246 • *Data distribution and scalability*: as clinical data is stored in different repositories, querying and retrieving data
247 becomes complex. Federated index registries manage these queries but introduce overhead in data synchronisa-
248 tion and cross-regional retrieval [17].
- 249 • *Security and privacy*: the system uses SOAP-based security mechanisms and HTTPS (Hyper-text Transfer
250 Protocol Secure) to protect patient data while anonymising sensitive information. However, ensuring consistent
251 security protocols across regions remains a challenge [17].
- 252 • *Legacy system integration*: many healthcare systems rely on legacy systems that are not designed for cross-
253 regional data exchange. Developing wrappers to ensure these systems can interact with newer federated archi-
254 tectures remains a key scalability challenge [17].

255 **Interoperability challenges in Federated systems** In federated health information systems like JA-InfAct,
256 several legal, organisational, semantic, and technical challenges emerged [18]:

- 257 • *Legal interoperability*: ensuring compliance with GDPR and other data protection laws was critical, with
258 anonymised, aggregated data shared across borders [18].
- 259 • *Semantic interoperability*: developing a Common Data Model to standardise coding systems like ICD-9 and
260 ICD-10 was a major challenge [18].
- 261 • *Technical interoperability*: differences in IT infrastructure and technical expertise across regions made deployment
262 of analysis pipelines difficult. Docker containers were used to ensure consistent software execution [18].
- 263 • *Organisational interoperability*: coordinating different health organisations required continuous communication
264 and trust-building. The Coordination Hub oversaw data model development and analysis execution [18].

265 Similarly, the federated model implemented in Austria addressed many of these same challenges [19]. The frag-
266 mentation of healthcare data, where information is dispersed across multiple providers, led to inefficiencies such
267 as duplicated tests and increased costs. The federated approach tackled these issues by virtually integrating data
268 repositories, allowing institutions to access and share information more effectively. Another significant challenge was
269 ensuring data privacy and legal compliance, as patient data remained locally stored, with only aggregated results or
270 metadata shared across the network. Ensuring secure, real-time data exchange between institutions, while complying
271 with privacy regulations like GDPR, remained a critical hurdle for healthcare systems adopting federated models [19].

272 **Blockchain challenges in Health Information Technology** Despite its potential, blockchain integration in
273 Health Information Technology faces significant challenges [16]:

- 274 • *Security and privacy vulnerabilities*: blockchain enhances data security but introduces privacy concerns, partic-
275 ularly with smart contracts and patient data [16].
- 276 • *Scalability and computational costs*: blockchain-based Health Information Technology systems require significant
277 computing power and transaction processing time, which limits scalability [16].

- *Data integration and compatibility*: interoperability between blockchain systems and existing legacy infrastructures poses challenges, requiring substantial IT overhauls [16].
- *User resistance and adoption*: blockchain adoption rates in healthcare remain low due to resistance and negative perceptions associated with cryptocurrencies. Education and stakeholder engagement are essential for improving adoption [16].

Blockchain interoperability in the Financial sector In the financial sector, the challenge of blockchain interoperability arises from differences in how various blockchain systems handle transactions, security, and asset ownership. One major challenge is scalability, as the low transaction throughput of major blockchains like Bitcoin (7 Transactions Per Second) [20] and Ethereum (14 Transactions Per Second) limits cross-chain operations [21]. Financial systems often rely on centralised notary schemes for secure cross-chain operations, introducing risks of single points of failure. Trustless relays and blockchain-agnostic protocols are being developed to mitigate these risks. For instance, RenVM, a decentralised custodian system, uses a Byzantine Fault Tolerant network to facilitate secure asset transfers without centralised intermediaries [21].

3.3 *Technical barriers to Interoperability*

A major challenge is the lack of standardisation across blockchain systems [1]. Unlike traditional financial systems that operate under standardised protocols, blockchain networks like Bitcoin and Ethereum operate independently, with distinct consensus mechanisms, transaction models, and security layers. This fragmentation creates barriers to interoperability, as systems cannot easily communicate or share data across chains. For example, consensus mechanisms such as Proof of Work (PoW), Proof of Stake (PoS), and Delegated Proof of Stake impose different requirements for transaction validation and block generation, which can hinder the seamless flow of assets or information between networks [22]. Furthermore, the scalability issues inherent in blockchains, such as low throughput and high latency, add another layer of complexity, particularly when handling large-scale systems with frequent transactions [22].

In the context of federated learning systems, integrating blockchain for decentralised data management exacerbates these challenges. Each blockchain system operates its own trust and security mechanisms, which are not always compatible across platforms. For instance, using different validation and aggregation mechanisms for model updates in federated learning introduces additional challenges, as data from nodes in one blockchain network may not easily integrate with another without significant modification [22].

To address these issues, blockchain-agnostic protocols, such as the Interledger Protocol aim to create an abstraction layer that enables cross-chain communication and asset migration without altering the underlying infrastructure [21]. However, this still requires overcoming technical barriers like network congestion, data integrity, and ensuring that malicious participants in one system cannot exploit vulnerabilities in another [22]. Additionally, security mechanisms like proof of elapsed time and local differential privacy used in federated learning need to be harmonised across blockchains, adding further technical complexity [22].

3.4 *Potential technical solutions*

Blockchain technology offers a potential solution to many of these challenges by enabling a distributed ledger that ensures the integrity and traceability of healthcare transactions [14, 1]. Beyond simply securing data, blockchain can integrate with other emerging technologies to address broader interoperability issues in healthcare. For example, federated learning offers a decentralised approach to training machine learning models on healthcare data without exposing sensitive patient information. This approach is particularly beneficial for maintaining patient privacy across healthcare networks while still enabling data-driven insights [22]. In a blockchain-empowered federated learning system, model updates are shared across a distributed ledger, ensuring that no central authority can compromise the system's security or accuracy. The use of smart contracts within blockchain can automate these processes, improving efficiency and transparency in healthcare data management [22].

Similarly, IoT devices, which are increasingly used in healthcare for patient monitoring, can benefit from a combined federated learning and blockchain architecture. IoT devices produce large amounts of real-time data that can be processed locally and securely shared via a blockchain network. This architecture allows for seamless communication across devices and systems without compromising data integrity or patient privacy [22]. Furthermore, the consensus mechanisms inherent in blockchain ensure that even in a decentralised network, data is consistently validated and securely stored [22].

Despite these advancements, challenges such as regulatory compliance, interoperability with legacy systems, and scalability must be addressed before blockchain can be fully implemented across the healthcare sector [14]. For instance, as blockchain and federated learning systems scale, issues like network congestion, storage pressure, and computational overhead need to be mitigated, possibly through off-chain storage solutions like Interplanetary File System or other distributed systems [22]. In addition, ensuring that different blockchain and IoT standards can work together seamlessly remains a critical barrier to widespread adoption in healthcare [22].

3.5 Semantic barriers to Interoperability

One of the most significant challenges in achieving interoperability across various domains is the lack of a universally accepted definition, which complicates efforts to establish coherent systems that can seamlessly interact [1]. Interoperability, while broadly referring to the ability of entities to exchange and make use of information, is subject to multiple interpretations depending on the context and application domain. This inconsistency arises because interoperability spans technical, organisational, and semantic layers, each with varying degrees of complexity. The absence of a unified definition has been attributed to the diversity of these domains and the unique requirements they impose on system interactions. As a result, definitions often lack precision and fail to provide universally applicable guidelines, contributing to a fragmented understanding of what it means for systems to be interoperable. In literature, this manifests in a wide variety of definitions and frameworks, with no single, agreed-upon approach dominating discussions across industries [23, 24, 8, 11].

This issue becomes even more pronounced when dealing with data interoperability, where disparate data models, schemas, and terminologies must be aligned to facilitate effective communication between systems [25]. The complexity of managing semantic heterogeneity—where the same data can be represented using different structures, labels, and formats—poses a substantial barrier [23, 24]. Data silos exacerbate this problem by keeping datasets isolated within specific systems, making it difficult to integrate or share information across platforms. Silos prevent the free flow of data, which is essential for ensuring that different systems can work together effectively. Without integration, valuable information remains locked within individual systems, unable to contribute to broader analyses or collaborative efforts. The process of database integration, for example, often involves reconciling different data models, each with its own semantic conventions. This can result in challenges such as terminological conflicts (e.g., when two databases use different labels for the same entity) and structural discrepancies, such as the representation of the same object in different ways. In federated database systems, these discrepancies must be addressed through mappings that transform data into a common model [24]. However, when data remains siloed, this reconciliation process becomes even more complex and time-consuming, making it harder to achieve true interoperability across systems. In sum, data silos are detrimental because they hinder the alignment of data models and prevent the realisation of seamless, interoperable systems.

Furthermore, semantic barriers complicate data interoperability because entities must not only exchange data but also understand and use it in meaningful ways. When the semantics of data—such as its intended meaning or the relationships between data points—are not clearly defined or are inconsistent across systems, interoperability becomes difficult to achieve. The process of semantic enrichment, where schemas are augmented with additional information to clarify meanings and relationships, is a critical step in overcoming these barriers [24]. However, this process is often manual and requires deep domain knowledge, further exacerbating the challenge of establishing interoperability [23, 24, 26]. Thus, the dual problems of semantic ambiguity and lack of standardisation significantly hinder efforts to create interoperable systems, particularly in complex, data-rich environments like healthcare or distributed information systems [23, 25, 26].

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