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Research Article

Towards an Integrated Model of Interoperability for Spatial Data Infrastructures

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Abstract
Although there is a vast literature available on interoperability models, and their respective interoperability levels, limited research has been carried out on the development of interoperability models for the implementation of Spatial Data Infrastructures. This article demonstrates the important role of metadata elements in the formalisation of interoperability models for the implementation of Spatial Data Infrastructures. It describes an approach for designing an integrated interoperability model based on the definition of a common template that integrates seven interoperability levels. They are: technical, syntactic, semantic, pragmatic, dynamic, conceptual and organisational levels. A non-hierarchical structure is proposed to ensure the relationship among these interoperability levels.

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1 Introduction

Information system interoperability occurs at multiple levels within and across platforms, providing the capacity of interchanging data, services, and applications among different organisations as well as users (Arms et al. 2002, Gordon 2003). Several interoperability levels have been proposed to achieve system interoperability, including technological, syntactic and semantic levels (ISO 2002, Tolk 2003, Turnitsa and Tolk 2006). In a Geographic Information System (GIS) context, interoperability has emerged as a research issue on computation implementations of geographical data exchange since a decade ago when eight interoperability levels were identified: these being the information community and institution, enterprise, application tools, middleware, data store, distributed computing environment and network (Goodchild et al. 1997). In a Spatial Data Infrastructure (SDI) context, the Open Geospatial Consortium (OGC) and International Organisation for Standardisation (ISO) TC211 have played a major role in improving Geodata and System Interoperability through the specification of object models and XML schemas to store and transfer data, Open Service Interfaces, and data and services metadata standards.

The formalisation of interoperability models became essential for developing abstractions of critical measures for the connectivity of different interoperability levels. NATO (2004) defined the first interoperability model in the NATO C3 System Architecture Framework (NC3SAF) based on the general directive of architecture development of systems, whereas SEI (Software Engineering Institute, Carnegie Mellon University) has proposed several interoperability models such as the LISI (Levels of Information System Interoperability), LCIM (Levels of Conceptual Interoperability), SOSI (System of System Interoperability) and the LCI (Levels of Coalition Interoperability) (Tolk 2003). Although there is a vast literature available on interoperability models, and their respective interoperability levels, very limited research has been carried out on the development of interoperability models for the implementation of Spatial Data Infrastructures (Groot and McLaughin 2000, Bernard et al. 2005).

In particular, there is no reference to our knowledge of the use of spatial metadata elements within interoperability models. Metadata elements have previously been defined as "data about data" (Kildow 1996; ANZLIC 1996, 1997). They have also been regarded as necessary specifications of a formalism in order to get automated access to the geospatial data (Najar and Giger 2006), which in turn, enables the interoperability of systems (Nebert 2004). Up to now, they have been successfully used to organise and maintain the investment made by an organisation and have provided information to data catalogs, clearinghouses and data transfers (Nogueras et al. 2005).

This article aims to demonstrate the important role of metadata elements in the formalisation of interoperability models for the implementation of Spatial Data Infrastructures. The research challenge is two-fold: (1) to define interoperability levels developed for application to static non-geographic data in a geographic domain; and (2) to integrate these levels of interoperability into an integrated model that facilitates the data, services, and applications exchange among Spatial Data Infrastructures.

The remainder of this article is organised as follows. In Section 2, we elaborate upon the definitions of the concept of interoperability and its proposed levels, focussing on the research work carried out in the fields of ICT and GIS. Section 3 outlines our approach to develop an interoperability model, with emphasis on the pairwise relationships among interoperability levels. The interoperability model consisting of seven different levels is proposed in the context of Spatial Data Infrastructures. In Section 4, we demonstrate how spatial metadata elements have been classified into one or more interoperability levels of the proposed model. The results of the classification are discussed in Section 5. Lastly, concluding remarks and future research are provided in Section 6.

2 The Realms of an Interoperability Model

The aim of this section is to provide an overview of the definitions of interoperability and how different levels of interoperability have been proposed in the literature based on different criteria and purposes of use.

2.1 What is Information System Interoperability?

Several definitions have been given over time by standard and policy organisations, as well as researchers. They vary from focussing on system and hardware components to services. More recently, the organisational aspect has been introduced in the definition in order to introduce the procedures and culture of an organisation that allow the exchange and re-use of information. Overall, the definitions state interoperability as the ability of different types of computers, networks, operating systems, and applications to exchange and re-use data and information. Table 1 summarises the main aspects and measures related to the existing definitions of interoperability.

In this article, we consider the definition of interoperability as proposed by ISO (2002), in which interoperability is associated to one of the following tasks:

- Find information and processing tools, when they are needed, independent of physical location.
- Understand and employ the discovered information and tools, no matter what platform supports them, whether local or remote.
- Evolve a processing environment for commercial use without being constrained to a single vendor's offerings.
- Build upon the information and processing infrastructures of others in order to serve niche markets, without fear of being stranded when the supporting infrastructure matures and evolves.
- Participate in a healthy marketplace, where goods and services are responsive to the needs of consumers and where commodity channels are opened as the market expands sufficiently to support them.

2.2 The Underlying Interoperability Levels

The levels of interoperability are a set of criteria and associated processes for assessing information system capabilities and implementation in the context of the degree of interoperability required. Several levels have been proposed in the literature (see Table 2 for an overview). Although there are a large number of interoperability levels, it is very difficult to tell them apart because their classification is highly correlated, and their definitions have common characteristics with each other.

In general, fifteen levels of interoperability have been distinguished as follows: Semantic, Syntactic, Technical, Pragmatic, Organisational, Schematic or Structural,

Table 1 Chronological view of existing definitions of interoperability

Source	Aspect	Measure
IEEE (1990)	*Systems or components of a system*	*Standards*
OpenGIS Consortium Technical Committee (1998)	*System or components of a system*	*OpenGIS Specifications*
Miller (2000)	*Systems, procedures and culture of an organisation*	*N/A*
Flater (2002)	*Quality of systems*	*N/A*
Rawat (2003)	*Network systems*	*N/A*
Gordon (2003)	*Software, data and solutions*	*Specifications*
NISO (2004)	*Difference hardware and software platforms, data structures, and interfaces*	*National Information Standards*
Woodley (2004)	*Different types of computers, networks, operating systems, and applications*	*Interoperability levels: Semantic, structural and syntactical*
ALCTS (2004)	*Systems or components of a system*	*N/A*
Kasunic and Anderson (2004)	*Systems, units, or forces to provide services*	*Service Specifications*
Taylor (2004)	*Systems*	*System Specifications*

Table 2 Chronological view of the mentioned references on interoperability levels

Model Acronym	ISO				Intermodel5			LCI	LCIM			IFEAD									Interop
Year	1990	1997	1997	1998	1999	1999	2000	2003	2003	2004	2004	2004	2005	2005	2005	2006	2006	2006	2006	2007	2007
Authors		Goh	Goodchild et al.	Bishr	Shanzhen et al.	Ouksel and Sheth	Miller	Tolk	Tolk and Muguira	Bermudez	Shekhar	Schekkerman	Stroetmann	Ding	Nowak	Mohammadi et al.	Kalantari et al.	van Assche	Turnitsa and Tolk	Dekkers	Chen and Daclin
Interoperability level																					
Technical	x		X			x	x		x			x				x	x		x	x	x
Schematic or structural		x	X	x		x					x				x						
Semantic	x			x	x	x	x		x	x	x	x	x	x	x		x		x	x	x
Organisational			X		x			x				x				x				x	x
Physical																		x			
Empirical																		x			
Syntactic	x		X	x	x	x			x		x		x	x	x			x	x		x
Pragmatic			X		x	x			x									x	x		
Social						x										x		x			
Political or Human							x									x					
Legal			X				x									x	x				
International							x														
Dynamic			X		x	x													x		
Conceptual			X						x										x		

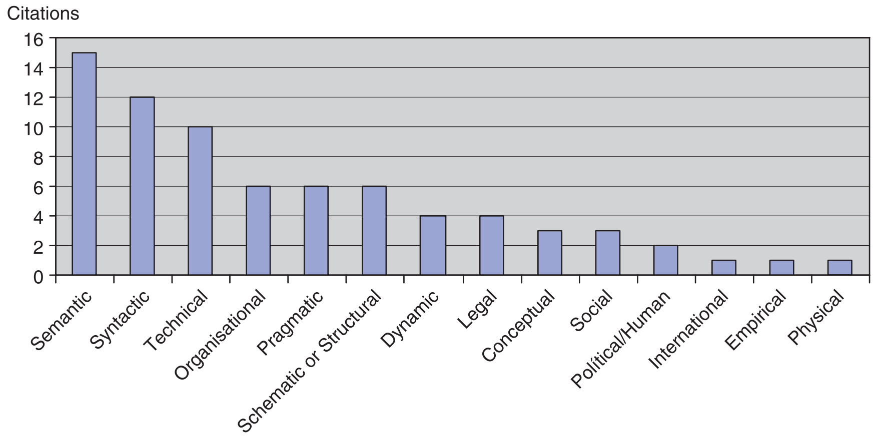

Figure 1 Citation frequency as a measure of research activity in interoperability

Dynamic, Legal, Conceptual, Social, Intercommunity, Political/Human, International, Empirical, and Physical. Figure 1 illustrates how often these levels have been mentioned in the literature. It is important to notice that the International, Empirical, and Physical levels have been cited by only one author; whereas the Semantic interoperability level is the most referred to in the literature, followed by the Syntactic, Technical, Organisational, Pragmatic, and Schematic or Structural levels, respectively. The remaining interoperability levels have been rarely mentioned in the literature.

2.3 Types of Interoperability Models

Within the research domain of information systems, interoperability models define a common taxonomy that allows meaningful discussion and analysis of different levels of interoperability. The Software Engineering Institute (2007) has pointed out the potential benefits of interoperability models as being one of the following:

- Define a common vocabulary that allows meaningful discussion and analysis;
- Provide hints regarding the structure of solutions; and
- Serve as a basis to evaluate new ideas and assess different options.

The selection of the interoperability levels and how they are related to each other determine the type of interoperability model. Nell (1996) has recognised the unified, federated and integrated models of interoperability. The unified models assume that there is a common metalevel template across constituent interoperability levels, providing a means for establishing semantic equivalence. Using the metamodel, any interoperability level can be translated into any other. Normalised semantics is established by owners of constituent interoperability levels. The ISO/IEC JTC1 Semantic Unified Metamodel, SUMM, is an example of a unified model template. With federated models there is also a common meta-level template, but in this case, the interoperability levels are required to be dynamically accommodated into the model rather than having a pre-determined metamodel. Federated models in a name space are identified as the most difficult defining problem in process interoperability.

With integrated models there is a common template where separate interoperability levels are associated to make into a coherent whole. Each interoperability level performs

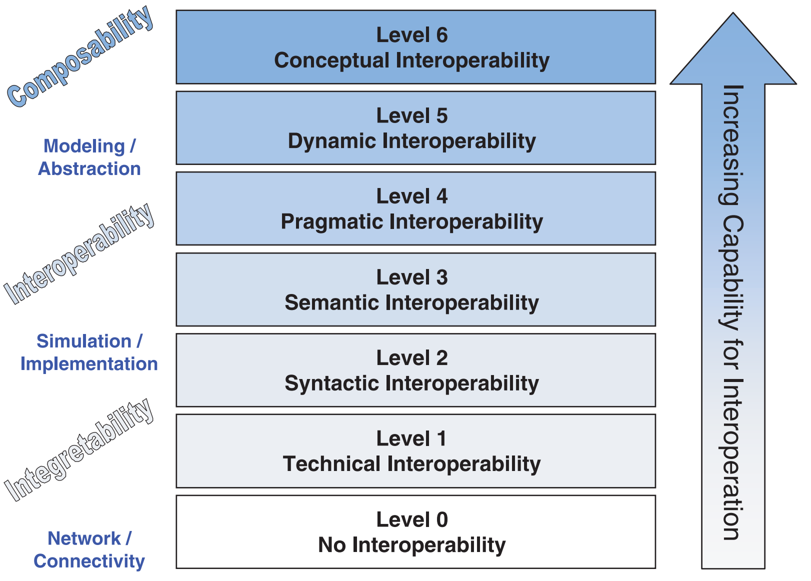

Figure 2 The integrated interoperability model proposed by Turnitsa and Tolk (2006)

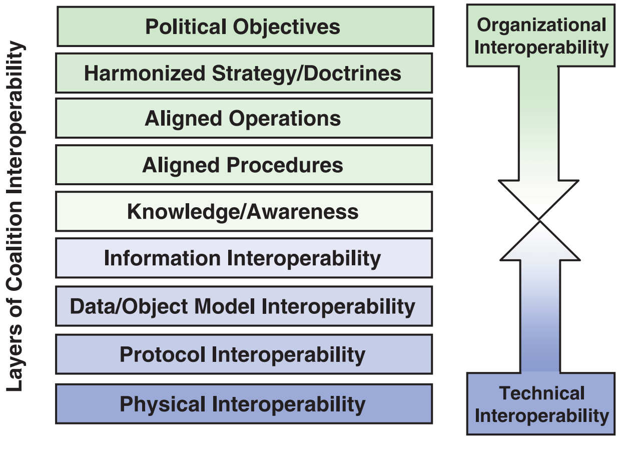

Figure 3 The Coalition Model (from Tolk 2003)

separate functions with communication and data sharing being performed by standardised routines and using common databases. The integrated approach is usually based on the creation of a hierarchical relation among the interoperability levels that represent the degree of capability for interoperation. The result is the creation of a hierarchical relation between the interoperability levels that represent the degree of capability for connectivity (Figure 2).

Tolk (2003) has also proposed the Coalition Model in which different aspects are needed for implementing the relations between the interoperability levels (Figure 3). He also stresses the important role of a common unified language for the integration of the interoperability levels from technical up to organisational.

Table 3 Integrated interoperability models in GIS (adapted from Goodchild et al. (1997) and Shanzhen et al. (1999))

System	Interoperability characteristics
Institution or information community	Policy, culture, value
Enterprise	Agreements, consensus
Semantics	Semantics translator, metadata Geographic information formalisation system
Service, Application,	Cooperation, coordination, services,
Tools, Middleware	Distributed objects, OpenGIS
Resource	Data, virtual database,
Transformation, Data store	MultiDatabase OGC warehouse framework
Resource discovery	Metadata, digital libraries, catalog, clearinghouse

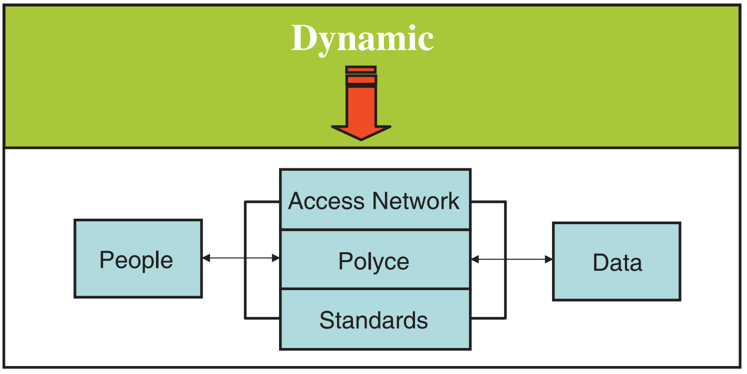

Figure 4 The components of SDIs (from Rajabifard and Binns 2004)

In a GIS context, the proposed integrated models are also based on a hierarchical relation of interoperability levels (Table 3). Shanzhen et al. (1999) actually suggests the use of metadata attributes for resource discovery and semantic systems.

Integrated models based on non-hierarchical structures open up new research issues since an overview of the structural as well as the specific composition of the various interoperability levels should be defined by users. Users are required to predetermine the interoperability levels and place procedures and measures for the necessary communication to occur within an application domain. In the SDI context, integrated models of interoperability are currently non-existent although users already have to deal with data through dynamic access networks, standards and policies (Williamson et al. 2003). Figure 4 illustrates some components of SDIs.

At the moment, users need to access data in a transparent mode, and as a result, both technical and semantic levels of interoperability are usually defined in order to support an access network, which in turn, can enable systems to communicate. Moreover, standards and specifications are being used to ensure syntactic, pragmatic and semantic interoperability. Organisational interoperability is mostly defined by organisations through their data policies. Data access is related to most of the interoperability levels. Conceptual interoperability is achieved through data models; meanwhile semantic interoperability is achieved through the meaning of data. In contrast, grammar is being used to encapsulate data for syntactic interoperability. The dynamic context of SDI is definitely related to the dynamic and pragmatic levels of interoperability. Both levels enable SDI users and compound services agents to locate and couple data services.

3 Common Template for Interoperability

Any integrated model scenario should assume the non-feasibility of successfully and globally defining the measures for the association across all interoperability levels. Our proposed approach is based on the definition of a common template that integrates interoperability levels. The degree of successful integration will not depend on a hierarchical structure of these levels. On the contrary, a non-hierarchical structure is proposed to ensure the integration among interoperability levels.

We propose a common template which is supported by the types of interoperability proposed in the literature, with the aim of defining an appropriate taxonomy of types of interoperability within the SDI context. This common template will enable us to carry out a multi-relational analysis based on different metadata elements that are relevant in the SDI context.

We will begin our analysis with the least mentioned types of interoperability:

- The physical and empirical interoperability layers proposed by van Assche (2006) deal with the aspects related to e-learning and they have a bearing on the aspects of interoperability related to the interaction between man and machine in the learning process, and in the amount and variety of information offered to the student in the setting of online teaching. They are pertinent only in this domain and not in the SDI context.
- The levels of international, political/human, social/cultural, intercommunity and legal interoperability may be incorporated as aspects involving the institution and/ or the organisation. The legal aspects are in many instances beyond the competence of the institutions since they are imposed by regulations coming from higher authorities, such as the national laws for communities and regions and the international laws for nations. The cooperation is an aspect affecting both institutions and organisations, allowing them to define the interrelations at the regional, national, intercommunity and international level. Taking into account these views and the relevance of the opinions and conclusions of the expert group, who mention this type of interoperability as the most difficult to reach (Goodchild et al. 1997), these aspects have been included in a sole level under the name of 'organisational'.
- The schematic or structural aspects mentioned by Goh (1997), Shekhar (2004), and Nowak and Nogueras (2005) may have already been included in other types of interoperability. As an example, Nowak (2005) identifies a lack of schematic or structural interoperability among the different data models. This lack of interoperability may also be considered as a lack of conceptual interoperability, since in many cases the definition of the data model is not described with modelling languages that would make the model independent of its implementation. Goh (1997) and Shekhar

(2004) also deal with these aspects, even though they might be deemed syntactic and conceptual aspects – when we consider the data and metadata models as mechanisms that allow sharing the data schemes.

Therefore, a common template consisting of seven interoperability levels has been defined in our proposed integrated model. They are: technical, syntactic, semantic, pragmatic, dynamic, conceptual and organisational:

1. **Technical Interoperability:** Like Turnitsa and Tolk (2006), we define technical interoperability as the one enabling the interconnection of systems through common communication protocols allowing information exchange at its most basic level: bits and bytes. The aspects making technical interoperability possible are those of the systems that get interconnected, both at the hardware and software level (IDABC 2006), the communication infrastructure, the communication protocols allowing both systems to establish communication and information exchange, regardless of format, meaning of the information and distributed computation capability. It copes *with hardware and firmware requirement and lower communication protocols, referred to as means of integration enabling integratability of components* (Antonovic and Nowak 2006, Yilmaz and Tolk 2006). We have identified some examples related to SDI, including character sets, character encoding, file identifiers, computer environment descriptions, file names, services types and version, transfer size, format name and versions, medium name and density, links, and protocols.
2. **Syntactic Interoperability:** Syntactic interoperability is about the information exchange between systems by using a common data format or structure, language, logic, registers and files. Aspects allowing syntactic interoperability include the standards or format specifications which structure information, so that the information could be processed and interpreted. Thus the XML formats together with the data schemas (XSD or DTD) or the widely used standardised graphic formats (JPEG, TIFF, PNG) may be regarded as elements supporting syntactic interoperability. We have identified most of the OGC XML Schemas for Web applications and Web Services (WFS, WCS, CS-W, WPS, SOS), data encoding languages (GML, O&M, SensorML, TML), defining portrayal Styles (SLD) and filtering features encoding language (FE).
3. **Semantic Interoperability:** Semantic interoperability is about information exchange using a shared, common vocabulary that avoids inaccuracies or mix-ups when interpreting the meaning of terms. Mechanisms or tools supporting semantic interoperability are the standards or specifications defining information exchange schemas and the unambiguous meaning of every element. Some references to mechanisms supporting semantic interoperability include the *Web Service Description Language* (WSDL) and the *Simple Object Access Protocol* (SOAP) at the level of service interconnection, the *Geographic Mark-Up Language* (GML) for the transfer of vector GI, the *Style Layer Description* (SLD) for definition of a visualization style, the *Common Query Language* or *Filter Encoding* (ISO19143) for queries and filters. Most of ISO 191xx standards include a common vocabulary and a great number of controlled lists of terms that can help to share a common meaning. The Metadata standard ISO19115 contains almost 24 code and enumeration lists. Finally, the INSPIRE initiative is defining some rules to classify spatial data themes into topic categories and semantic coding for services types (INSPIRE Metadata IR 2008).
4. **Pragmatic Interoperability:** Pragmatic interoperability is about interconnected systems knowing each other, so they are able to exploit application/services interfaces,

to invoke methods or procedures, and handle the data they need to exchange with other systems. An important aspect of this type of interoperability is that it makes system negotiation possible. In order to reach this type of interoperability, it is required for the service interfaces to be flawlessly defined. It is also required that both the methods that can be invoked and the data to be exchanged be known. Mechanisms supporting pragmatic interoperability are the standards and service specifications and/or applications such as the Standard ISO19128 (Web Map Service Interface), ISO19142 (Web Feature Service), and the OGC service specifications (WCS, CS-W, SOS, WNS, WAS, LSB). The OGC Services shares a common operation *getCapabilities* that enables other services to query the capabilities of the service in terms of implemented operations and get access to point of services.

5. **Dynamic Interoperability:** The dynamic interoperability allows the systems to monitor the running of the other systems and to respond to the changes in the transfer of information by taking advantage thereof. Aspects of dynamic interoperability are the service dynamic exchange capability, the possibility of switching from the use of one service to another, if the former does not cover the required needs or it is no longer available. To that effect, the systems have mechanisms allowing them to monitor the functioning of the network and other services and at the same time to be able to dynamically discover the existence of services complying with the requirements called for. This level entails a powerful semantic component supporting service discovery based on information describing services (service metadata). At this level, the INSPIRE Metadata Implementation Rules (IR) regulate the use of the value domain of spatial data service types such as discovery, view, download, and transformation. They are also invoked in such a way that a service type can be identified (OGC:CSW, OGC:WMS, OGC:WFS, OGC:WCS, OGC:WCTS, and OGC:WPS). Finally, INSPIRE has also classified spatial data themes annex of Directive 2007/2/EC into a topic category metadata element for keeping the reliability of dynamic service interchange (INSPIRE Metadata IR 2008).
6. **Conceptual Interoperability:** Conceptual interoperability is about knowing and reproducing the functioning of a system based on documentation usually articulated in a format as used in Engineering. Aspects of conceptual interoperability are those describing data and system model in the shape of standardised and interchangeable documentation from an engineering viewpoint, regardless of the model utilised to describe it. Description by means of UML, the data model from a repository of data sets or the model provided by a service makes this type of interoperability possible. Some standardised services of OGC such as OGC-WFS can provide a conceptual description of the features managed as a response to a *describeFeatureType* request. In this case, the conceptual description is retrieved in the GML Application schema format. On the other hand, organisations are also using Modelling or CASE tools that can interchange class diagrams (UML), restrictions, and comments based on a common format such as XMI (XML Metadata Interchange), which in turn, is independent of the CASE tools.
7. **Organisational Interoperability:** The organisational interoperability allows knowledge of business targets, process models, regulations and policies of access and use of data and services (SAGA 2006). We should also mention the aspects related to expectations, contracts and culture. Aspects of organisational interoperability are the knowledge and understanding of the policies of access and use of data and/or services, the personal or institutional responsibilities, the objectives and goals pursued by the organisation when creating data or providing services. Most of this knowledge

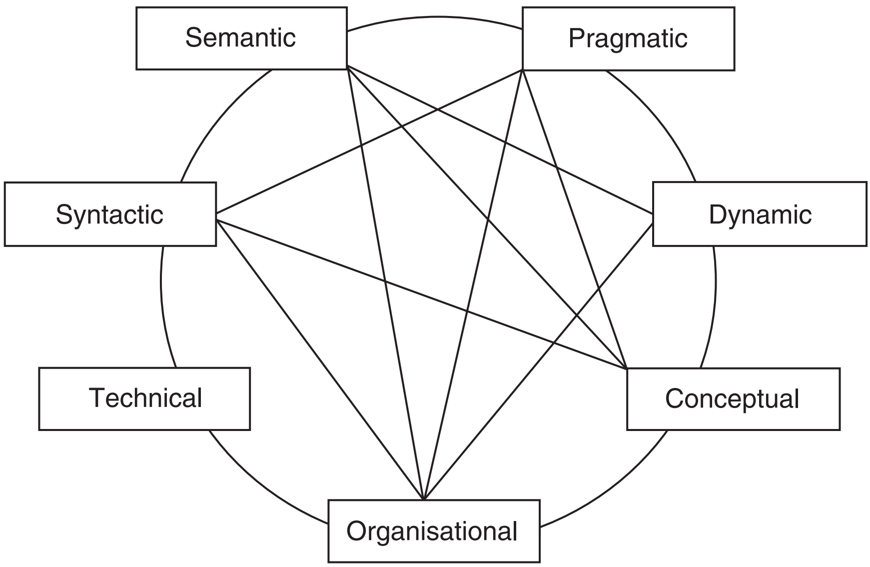

Figure 5 The common template for our integrated interoperability model

about goals, responsibilities, access and use polices are considered as constraint or identification information that is useful to evaluate use of metadata elements.

Concerning the existing relationships between the different levels of interoperability, we argue that they are not necessarily hierarchical, as proposed in the literature. Our hypothesis is the existence of different types of relationships – not only hierarchical – between the different levels of interoperability (Figure 5). As an example, our assumption is that in order to reach the conceptual interoperability, for which the data models and the application schemas are most important, the syntactic and semantic interoperability are necessary, although the pragmatic or dynamic interoperability levels do not appear to be needed. We could find another example with regard to legal issues, such as intellectual property and use constraints. In order to be able to handle these issues, a syntactic and semantic interoperability is required, but that is not the case for the conceptual, dynamic or pragmatic interoperability. Both examples reveal that the dependency relationships between the levels of interoperability are non-hierarchical in nature.

As the outcome of this common template and its use in the documentation of datasets, as well as relying on the Intermodel5 Model proposed by Shanzhen et al. (1999) – where at least two interoperability roles for the metadata were suggested (resource discovery and semantics) – it is our premise that metadata elements can be used to implement such relations of interoperability levels of an integrated model, which in turn, will uphold our hypothesis.

4 Classification of Metadata Elements

The metadata elements have been classified accordingly to an interoperability level of our integrated model. In this section, we summarise the classification carried out for the

ISO 19115–19139 metadata elements. The ISO19115 metadata standard foresees a high, variable number of elements that may reach up to 400. In order to be consistent with the standard, we have opted for the structure in packets and elements classes. Spreadsheets have been used to show the element names together with a brief description. In addition, every element of the standard has been classified into one or more interoperability levels. Finally, for the standard core elements – and in many other cases – a textual justification of the adopted classification has also been provided.

4.1 The Criteria Used for the Classification

Table 4 shows an example of classification for the packet of metadata elements named as MD_Metadata. The first column indicates the name of the metadata element designed by ISO in its standard, the second column indicates the description of the element, and the next seven columns indicate the different possible interoperability levels for that particular metadata element. The boxes identified in red indicate that the metadata element is mandatory, according to the standard. The cells in orange identify conditional metadata elements.

4.2 The Relationships between Interoperability Levels

We have considered pair-wise relationships between interoperability levels to achieve a coherent grouping of metadata elements. These relationships support a non-hierarchical structure of interoperability levels that can also reveal the interchange intensity between them. Indeed, if we have relationships fixed and keep adding or subtracting metadata elements, the classification process will change the intensity of the existing relationships. The ideal situation will be when all relationships between interoperability levels are in equilibrium. For example, existing weak relationships might have an increase of intensity due to new metadata specifications. Table 5 summarises some of the main aspects of the pair-wise relationships within our integrated interoperability model.

5 Results and Discussion

The objective here is to show the results of the classification of the metadata elements marked as 'core' in the metadata standard ISO 19115. Table 6 illustrates an example of the classification carried out to identify the types of interoperability supporting each one of the ISO 19115 core metadata elements. The same classification procedure has been applied to the all the remaining ISO19115 metadata elements. Unfortunately, the number and length of the results means it is not possible to display all of the results in tables in this article.

5.1 The Overall Classification Results

The overall results of the classification of the ISO19115 core metadata demonstrate the current emphasis on semantic, dynamic and organisational interoperability levels within our integrated model (Figure 6). The existence of a large number of metadata elements for each of these interoperability levels imposes requirements for semantic equivalence across the other interoperability levels as well. Therefore, our integrated model has

Table 4 Metadata classification schema

Packet Element	MD_Metadata Description	Technical	Syntactic	Semantic	Pragmatic	Dynamic	Conceptual	Organisational
fileIdentifier	unique identifier for this metadata file	x			x			
Language	language used for documenting metadata			x				x
characterSet	full name of the character coding standard used for the metadata set	x		x				
ParentIdentifier	file identifier of the metadata to which this metadata is a subset (child)	x			x			
hierarchyLevel	scope to which the metadata applies			x			x	x
hierarchyLevelName	name of the hierarchy levels for which the metadata is provided							x
contact (CI_ResposableParty)	*party responsible for the metadata information*							
dateStamp	date that the metadata was created			x		x		x
metadataStandardName	name of the metadata standard used		x	x				x
metadataStandardVersion	version (profile) of the metadata standard used		x	x				x
dataSetURI	Uniformed Resource Identifier (URI) of the dataset to wich the metadata applies	x		x	x			
locale (PT_Locale) (ISO19139)	*Information about linguistic alternative*							
spatialRepresentationInfo (MD_SpatialRepresentation)	*digital representation of spatial information in the dataset*							
referenceSystemInfo (MD_ReferenceSystemInfo)	*description of the spatial and temporal reference systems used in the dataset*							
metadataExtensionInf (EX_Extent)	*information describing metadata extensions*							

Table 4 *Continued*

Packet Element	MD_Metadata Description	Technical	Syntactic	Semantic	Pragmatic	Dynamic	Conceptual	Organisational
identificationInfo (MD_identification)	*basic information about the recource(s) to which the metadata applies*							
contentInfo (MD_ContentInformation)	*provides information about the feature catalogue and describes the coverage and image data characteristics*							
distributionInfo (MD_Distribution)	*provides information about the distributor od and options for obtaining the resource(s)*							
dataQualityInfo (DQ_DataQuality)	*provides overall assessment of quality of a resource(s)*							
portrayalCatalogueInf (MD_PortrayalCatalogueReference)	*provides information about the catalogue of rules defined for the portrayal of a resource(s)*							
metadataConstrains (MD_Constraints)	*provides restrictions on the access and use of metadata*							
applicationSchemaInf (MD_ApplicationSchemaInformation)	*provides information about the conceptual schema of a dataset*							
metadataMaintenance (MD_MaintenanceInformation)	*provides information about the frequency of metadata updates, and the scope of those updates*							
PT_Locale	Defines the locale in which the value (sequence of characters) of the localised character string is expressed							
language	Designation of the locale language			x				X
country	Designation of the specific country of the locale language			x				X
characterEncoding	Designation of the character set to be used to encode the textual value of the locale	x		x				

Table 5 Examples of pair-wise relationships between interoperability levels

Type of pair-wise relationship	Role in the SDI context
Technical vs. Pragmatic	Demonstrate the automated support for data/service access, exchange and communication
Technical vs. Dynamic	Allow the dynamic evaluation of the use of data and services
Syntactic vs. Pragmatic	Provide the description of data sets
Semantic vs. Technical	Inform about the storage support
Semantic vs. Pragmatic	Demonstrate status, constraints and representation type of the data sets
Semantic vs. Dynamic	Increase quality of results of service search
Semantic vs. Conceptual	Provide information about the context of data sets
Semantic vs. Organisational	Inform about roles and responsibilities
Organisational vs. Dynamic	Facilitates the use and re-use of data and exploitation of services
Pragmatic vs. Dynamic	Inform about the suitability of SDI

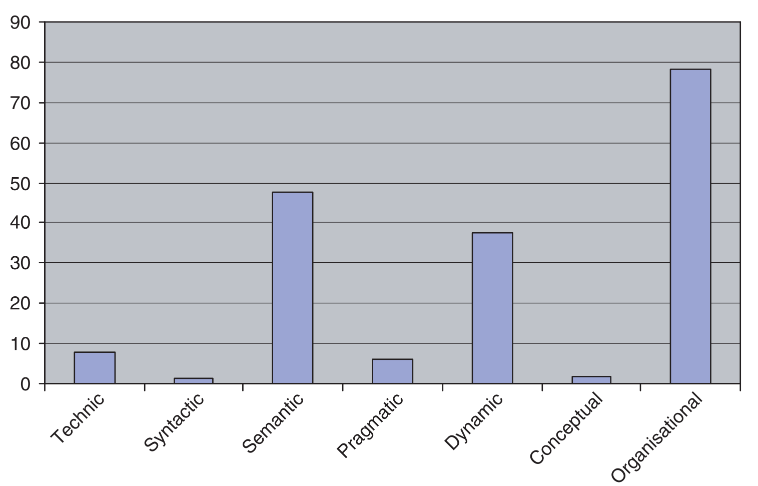

Figure 6 Overview of results of the entire classification of ISO19115 core metadata elements per interoperability level

contributed to establish the ISO19115 core metadata elements that might be present in all interoperability levels in the future.

Moreover, we have identified some metadata elements that promote technical interoperability, providing information useful to enable communication and data interchange. Some of them are: file identifier, character set, file name, protocol, linkage, transfer size, format name and version, medium name, density, and volumes. In terms of syntactic interoperability, our model has identified metadata standard name and version as the main metadata elements that handle this type of interoperability. In fact,

Table 6 Example of designated Interoperability levels of ISO 19115 Core Metadata

Metadata Elements	Mandatory/ conditional	Technical	Syntactic	Semantic	Pragmatic	Dynamic	Conceptual	Organisational	Results and Comments
fileIdentifier		x			x				**Technical:** identifier associated to the file and metadata file system. Intended to avoid maintenance and management problems in databases. **Pragmatic:** allows dynamic handling of metadata by identifiers: collection, maintenance.
Language				x				x	**Semantic:** term of a list identifying language of metadata. **Organisational:** enables language negotiation in business models.
characterSet		x		x					**Technical:** allows correct handling of bytes from the metadata register. **Semantic:** identifies univocally encoding type on the base of a list of controlled terms.
parentIdentifier		x			x				**Technical:** identifies univocally the parent node in the hierarchical relation and makes access to metadata possible. **Pragmatic:** allows automatically browsing through metadata relations

Table 6 *Continued*

Metadata Elements	Mandatory/ conditional	Technical	Syntactic	Semantic	Pragmatic	Dynamic	Conceptual	Organisational	Results and Comments
hierarchyLevel				x			x	x	**Semantic:** in the form of a controlled list, identification is made of which hierarchical level the metadata applies to. **Conceptual:** defines conceptually the element the metadata applies to: dataset, series, etc . . . **Organisational:** Allows structuring and negotiation of metadata granularity.
hierarchyLevelName								x	**Organisational:** defines name or identifier assigned to the dataset by the responsible organisation.
contact (CI_ResposibleParty)									
dateStamp				x		x		x	**Semantic:** allows correct interpretation of date. **Dynamic:** allows metadata filtering by date of creation. **Organisational:** preserves chronologically knowledge in the organisation.
metadataStandardName			x	x				x	**Syntactic:** defines syntax. **Semantic:** defines meaning of elements. **Organisational:** defines standard of metadata and its negotiation.

very few metadata elements were classified into the syntactical interoperability level. The results of the classification confirm that only six metadata elements have provided this type of interoperability.

In the ISO19115 Metadata Standard there are 24 code and enumeration lists (topic category, topological level, spatial representation type, metadata scope, restriction, progress, obligation, medium name and format, maintenance frequency, role, evaluation method, presentation form, online function, and data type) that provide common meaning and interpretation criteria, and as a result, they promote semantic interoperability.

A high number of metadata elements supporting the pragmatic interoperability level were not foreseen since the ISO19115 Metadata Standard is mainly developed for the description of datasets and to a lesser extent services. The pragmatic aspects are mainly related to the use of the methods exposed by the services. Therefore, the results of the classification indicate that only 24 elements were identified as supporting the pragmatic interoperability level.

We have classified the following metadata elements within the dynamic interoperability level: metadata date stamp, dataset status, spatial representation type, keywords, scale, access constraints and use limitations, spatial reference information, topologic level, dimension name and size, identifiers, format name and version. Fewer metadata elements have been identified at the conceptual level; they were hierarchy level, association and initiative type, schema and constraint language, schema ASCII and software development file format. Finally, several metadata elements have been identified at the organisational level, including the information related to business process and legal aspects. Some examples are: dataset and metadata language, dates, responsibilities, lineage, quality reports, security, legal and other constraints, purpose, and supplemental information.

5.2 The Interoperability Relationships

Concerning the relationships between the different levels of interoperability, the results have shown that they are not necessarily hierarchical in an integrated model. Table 7 summarises the total number of core metadata as well as all ISO 19115 metadata elements which have been used to determine the relationships among the seven interoperability levels proposed in our integrated model.

The results also demonstrate that the relations between interoperability do not exist among all levels according to the ISO19115 core metadata. For example, the syntactic and conceptual interoperability levels are currently the less related levels in our integrated model (Figure 7). New core metadata elements need to be defined in order to increase the intensity of such relations among these interoperability levels.

Figure 8 illustrates the results obtained from the classification of all metadata elements specified in the ISO19115 standard.

The metadata elements quantify the relational interchange intensity among different levels of our integrated interoperability model. However, they do not support 100% of the envisaged relations in the model yet. Specially, the ISO19115 standard is ineffective on the specification of metadata elements for the relations with the conceptual interoperability level. On the other hand, the interrelations among the organisational, semantic and dynamic are supported by over 25% of the current standard metadata specifications (Figure 9). It is important to notice that such a strong relation does not occur with any other interoperability levels.

Table 7 Metadata elements which define the relations between interoperability levels

	Technical	Syntactic	Semantic	Pragmatic	Dynamic	Conceptual	Organisational
(a) Core Metadata ISO 19915							
Technical	8	0	4	2	3	0	3
Syntactic	0	3	3	0	1	0	2
Semantic	4	3	40	0	28	1	29
Pragmatic	2	0	0	4	2	0	1
Dynamic	3	1	28	2	31	0	23
Conceptual	0	0	1	0	0	1	1
Organisational	3	2	29	1	23	1	43
(b) Metadata ISO 19915							
Technical	32	3	11	8	10	0	22
Syntactic	3	6	3	3	4	0	3
Semantic	11	3	196	4	127	6	181
Pragmatic	8	3	4	24	21	0	19
Dynamic	10	4	127	21	151	0	143
Conceptual	0	0	6	0	0	7	7
Organisational	32	3	181	19	143	7	229

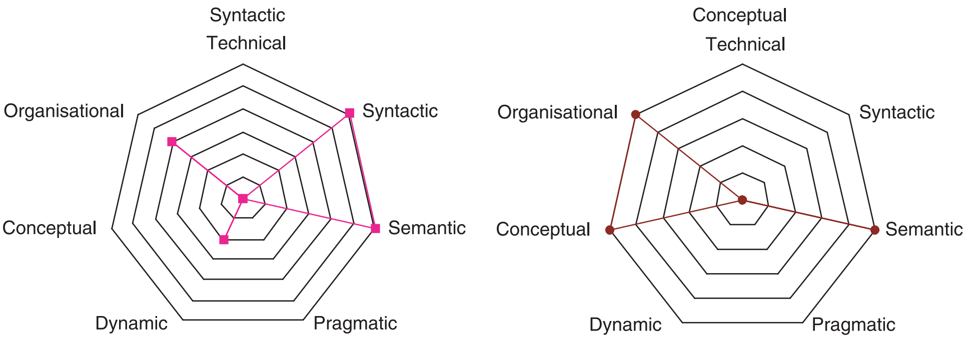

Figure 7 The pair-wise relations of syntactic and conceptual interoperability levels according to the ISO19115 core metadata

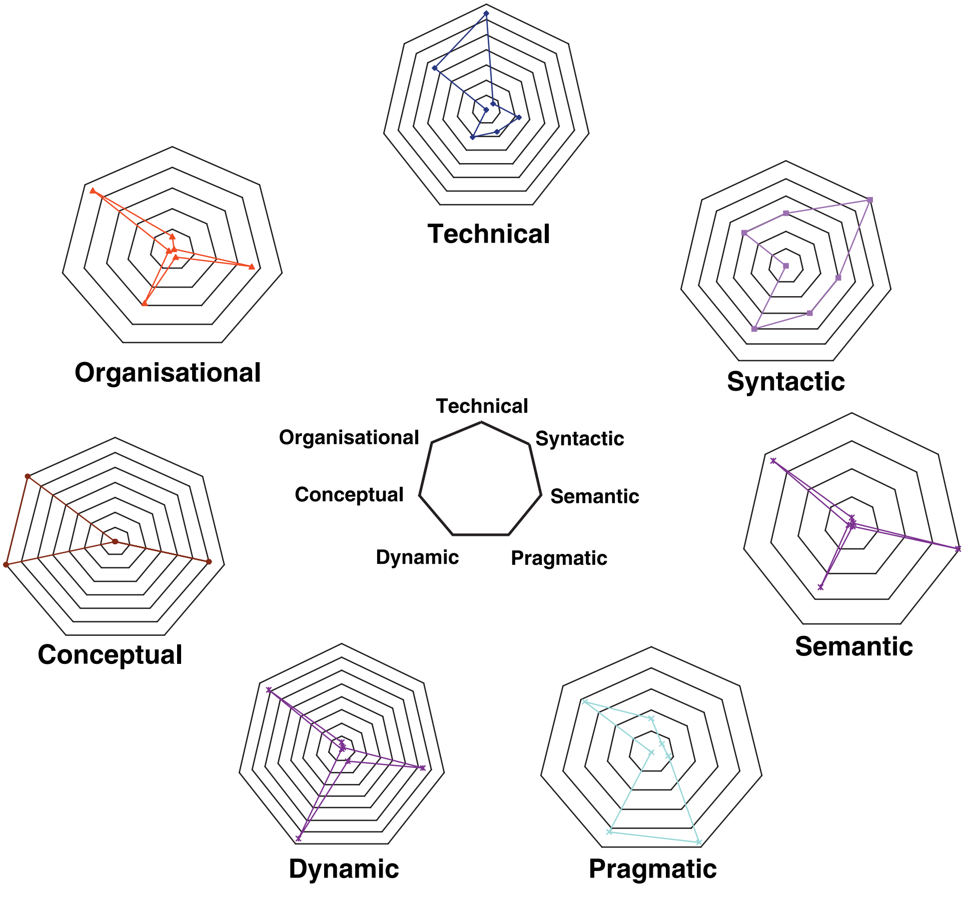

Figure 8 Overview of the results of the potential relations of interoperability levels according to the ISO19115 full metadata

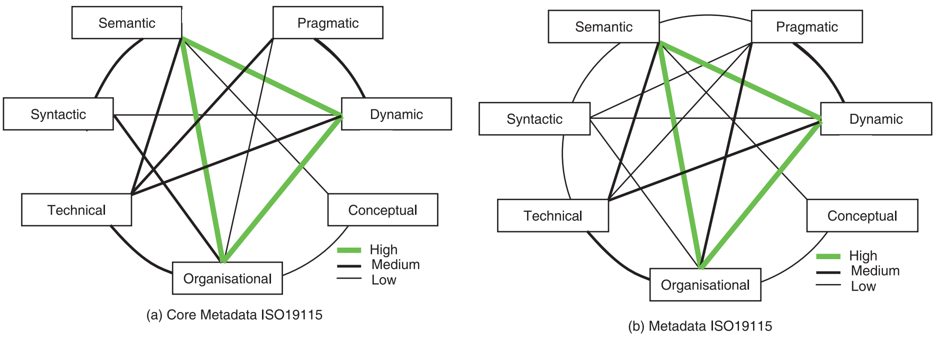

Figure 9 Overview of the resulting pair-wise relations of our interoperability model

6 Conclusions

One of the main reasons for developing integrated models is that by sharing a sound conceptualisation the potential misunderstandings and inconsistencies should be reduced. On the other hand, carrying out a sound and complete classification of metadata elements is far from trivial, and defining, evaluating, and adopting new measures is not an easy task. In addition, a global convergence to a small set of universally accepted interoperability levels is unlikely to occur soon and suggests that we will probably keep going with many heterogeneous, yet coexisting, interoperability levels. Nevertheless, at the current state of the art, and although Spatial Data Infrastructures are rapidly becoming a reality, the adoption of integrated models to address the interoperability issue will remain a research issue. Many kinds of difficulties hinder the acceptance of integrated models. Above all, we believe that the lack of awareness of what an integrated model is, why it is important, and how it could be used, constitute the most significant obstacles in supporting interoperability models in the SDI context. Integrated interoperability models can help developers of Spatial Data Infrastructures to deliver better services. We hope this article will achieve this understanding.

The results have confirmed our initial hypotheses concerning the pair-wise relationships between interoperability levels. In the SDI context, a small number of metadata elements were concurrently classified into technical and syntactical, semantic, conceptual and organisational interoperability. The results of the classification have shown that no metadata element has been concurrently classified into all the five interoperability levels. This was expected since the aim of each one of these five types of interoperability is quite different (i.e. raw data interchange, formats, meaning and the qualities, models and aspects related to the business logic).

On the other hand, it was expected that a significant number of metadata elements would be concurrently classified into technical, pragmatic and dynamic interoperability levels. This hypothesis was based on the usefulness of the pragmatic aspects to achieve the exploitation of data and on the usefulness of the technical aspects to access data or exploit the services from the pragmatic point of view. The results of the classification have confirmed this hypothesis since there was 13.9% (21/151 – medium intensity) of elements supporting the dynamic-pragmatic relationship, and 28.5% (6/21 – medium intensity) that supported the dynamic-technical relationship.

In addition, since the objective of metadata is to document and facilitate the use of data, it would be rational to contend that the metadata elements supporting semantic interoperability can also support other types of interoperability, especially the dynamic interoperability. The results of the classification have shown that the metadata elements supporting semantic interoperability (196) also provide dynamic (127/196 – high intensity) and organisational (181/196 – high intensity) interoperability levels as well. Whereas the remainder of the values may appear barely significant – e.g. technical interoperability (11/196 – medium intensity) – the weight of these 11 elements within all of the elements supporting technical interoperability (33) has to be taken into account.

It is also interesting to point out that a high number of metadata elements have been found to concurrently provide the pair-wise relationship between the pragmatic and dynamic interoperability levels. The results of the classification have shown that 87% (21/24 – high intensity) of the metadata elements facilitate such a relationship. In contrast, the relationship between the pragmatic and conceptual interoperability levels is non-existent, since no metadata element has been concurrently classified at both types of interoperability levels.

Finally, an integrated interoperability model demonstrates that interoperability is much more than just connectivity among systems. The results illustrate that the interchange intensity among different interoperability levels through metadata elements is essential to support the integration. Therefore, users must predetermine the interoperability levels and place the metadata elements for the necessary integration to occur within an application domain. In other words, Spatial Data Infrastructures must of necessity be connected, but they may not be integrated. It is important to distinguish between these fundamentally different concepts of connectivity and integration, since failure to do so sometimes obscures the debate over how to achieve interoperability. For this reason, developing and applying precise interoperability measures, such as metadata elements, is vital for ensuring the integration of Spatial Data Infrastructures.

Future research work will be to verify the proposed integrated model, making sure that the metadata elements act as intended to integrate the interoperability levels that have been designed for. This will generally involve trying the integrated model against a number of information systems, such as historical GIS, territorial information systems, and spatial planning information systems.

References

ALCTS 2004 ALCTS/CCS/Committee on Cataloguing: Description and Access Task Force on Metadata, Summary Report. WWW document, http://www.libraries.psu.edu/tas/jca/ccda/tf-meta3.html

Antonovic V and Novak I 2006 GISOSS: One-stop-shop GIS. In *Proceedings of the Twenty-third FIG Congress*, Munich, Germany (available at http://www.fig.net/pub/fig2006/papers/ts37/ts37_02_antonovic_novak_0569.pdf)

ANZLIC 1996 *ANZLIC Guidelines: Core Metadata Elements Version 1 Report*. Canberra, ACT, Australian New Zealand Land Information Council Working Group on Metadata

ANZLIC 1997 Core Metadata Elements for Land and Geographic Directories in Australia and New Zealand. WWW document, http://www.auslig.gov.au/pipc/anzlic/metaelem.html

Arms, W Y, Dushay N, Fulker D, and Lagoze C 2002 A spectrum of interoperability: The site for science prototype for the NSDL. *D-Lib Magazine* 8(1) (available at http://www.dlib.org/dlib/january02/arms/01arms.html)

Assche F van 2006 An Interoperability Framework. WWW document, http://www.intermedia.uio.no/confluence/display/life/An+Interoperability+Framework

Bermudez L 2004 ONTOMED: Ontology Metadata Framework. Unpublished PhD Dissertation, Drexel University (available at http://dspace.library.drexel.edu/bitstream/1860/376/8/Bermudez_Luis.pdf)

Bernard L, Kanellopoulos I, Annoni A, and Smits P 2005 The European Geoportal: One step towards the establishment of a European Spatial Data Infrastructure. *Computers, Environment and Urban Systems* 29: 15–31

Bishr Y 1998 Overcoming the semantic and other barriers to GIS interoperability. *International Journal of Geographical Information Science* 12: 299–314

Chen D and Daclin N 2007 Barriers driven methodology for enterprise interoperability. In Camarinha-Matos L, Afsarmanesh H, Novais P, and Analide C (eds) *Establishing the Foundation of Collaborative Networks*. Boston, MA, Springer: 453–60

Dekkers M 2007 Metadata and Modelling for Interoperability. WWW document, http://library2.nalis.gov.tt/Portals/0/cdl_Makx_Dekkers_20070712.pdf

Ding H 2005 Challenges in Building Semantic Interoperable Digital Library System. WWW document, http://www.idi.ntnu.no/grupper/su/courses/dif8901

Flater D 2002 Impact of model-driven standards. In *Proceedings of the Thirty-fifth Hawaii International Conference on System Sciences*, Honolulu, Hawaii (available at http://csdl2.computer.org/comp/proceedings/hicss/2002/1435/09/14350285.pdf)

Goh CH 1997 Representing and Reasoning about Semantic Conflicts in Heterogeneous Information Sources. Unpublished PhD Dissertation, MIT Sloan School of Management

Goodchild M, Egenhofer M, and Fegeas R 1997 Interoperating GISs: Report of a Specialist Meeting held under the Auspices of the VARENIUS Project. WWW document, http://www.ncgia.ucsb.edu/Publications/Varenius_Reports/Interop.pdf

Gordon D 2003 What is Interoperability and Why Does It Matter? WWW document, http://resource.mapinfo.com/static/files/document/1074288321775/mapinfomag_summer2003.pdf

Groot R and McLaughin J (eds) 2000 *Geospatial Data Infrastructure: Concepts, Cases, and Good Practice*. Oxford, Oxford University Press

IDABC 2006 *Interoperability for eGovernment: European Interoperability Framework for Pan-European eGovernment Services*. Luxembourg, Office for Official Publications of the European Communities (available at http://ec.europa.eu/idabc/en/document/3473/5585)

IEEE 1990 *Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*. New York, Institute of Electrical and Electronics Engineers

INSPIRE Metadata IR 2008 Draft Guidelines: INSPIRE Metadata Implementing Rules Based on ISO19115 and ISO19119. WWW document, http://www.ec-gis.org/inspire/reports/ImplementingRules/metadata/Draft_Guidelines%20_INSPIRE_metadata_implementing_rules.pdf

Kalantari M, Rajabifard A, Wallace J, and Williamson I 2006 An interoperability toolkit for e-Land administration. In Williamson I, Enemark S, and Wallace J (eds) *Sustainability and Land Administration Systems*. Melbourne, University of Melbourne Department of Geomatics Research Report: 213–22

Kasunic M and Anderson W 2004 *Measuring Systems Interoperability: Challenges and Opportunities*. Pittsburgh, PA, Carnegie Mellon University Software Engineering Institute Technical Note No CMU/SEI-2004-TN-003

Kildow M 1996 The Value of Metadata (A NSDI report). WWW document, http://www.r1.fws.gov/metadata/meta.html

Miller P 2000 Interoperability: What Is It and Why Should I Want It? WWW document, http://www.ariadne.ac.uk/issue24/interoperability/intro.html

Mohammadi M, Binns A, Rajabifard A and Williamson I 2006 Spatial data integration. In *Proceedings of the Seventeenth UNRCC-AP Conference and Twelfth Meeting of the PCGIAP*, Bangkok, Thailand (available at http://www.geom.unimelb.edu.au/research/SDI_research/publications/files/Spatial%20Data%20Integration.doc)

Najar C and Giger C 2006 Spatial Data and Metadata Integration for SDI Interoperability. Unpublished manuscript

NATO 2004 *NATO C3 Board: NATO C3 System Architecture Framework (NAF)*. Brussels, North American Treaty Organization Document No AC/322-D(2004)0002 (INV)

Nebert D 2004 *Developing Spatial Data Infrastructures: The SDI Cookbook (Version 2.0)*. Washington, D.C., Federal Geographic Data Committee

Nell J D 1996 ISO TC184 SC5 WG1 Convenor Report and Meeting Minutes. WWW document, http://www.mel.nist.gov/sc5wg1/n380min.htm

NISO 2004 Understanding Metadata. WWW document, http://www.niso.org/standards/resources/UnderstandingMetadata.pdf

Nogueras-Iso J, Zarazaga-Soria F, and Muro-Medrano P R 2005 *Geographic Information Metadata for Spatial Data Infrastructures: Resources, Interoperability and Information Retrieval*. New York, Springer

Nowak J and Nogueras J 2005 Issues of multilingualism in creating a European SDI: The perspective for spatial data interoperability. In *Proceedings of the Eleventh EC-GI and GIS Workshop*, Alghero, Sardinia (available at http://www.ec-gis.org/Workshops/11ec-gis/)

Open GIS Consortium Technical Committee 1998 *The OpenGIS Guide: Introduction to Interoperable Geoprocessing and the OpenGIS Specification* (Third Edition). Wayland, MA, Open GIS Consortium

Ouksel A and Sheth A 1999 Semantic interoperability in global information systems: A brief introduction to the research area and the special section. *SIGMOD Record* 28: 5–12

Rajabifard A and Binns A 2004 Facilitating Virtual Australia Utilizing an SDI Enabled Platform. WWW document, http://datasmart.oesr.qld.gov.au/Events/datasmart.nsf/0/F0E6094FCB6E7F124A256FA2007C2274/$FILE/QLD%20Seminar-CRC-Project%203.1%20-%20Dec%202004.pdf

Rawat S 2003 Interoperable Geo-Spatial Data Model in the Context of the Indian NSDI. WWW document, http://www.itc.nl/library/Papers_2003/msc/gfm/sujata.pdf

SAGA 2006 Standards and Architectures for eGovernment Applications SAGA. WWW document, http://www.epractice.eu/document/3210

Schekkerman J 2004 Roadmap to Implementation. WWW document, http://web-services.gov/region4soa10104.ppt

Shanzhen Y, Li Q, and Cheng J 1999 An interoperability GIS model based on the spatial information infrastructure. In *Proceedings of the International Symposium on GeoInformatics and SocioInformatics*, Ann Arbor, Michigan: 1–5

Shekhar S 2004 Spatial data mining and geospatial interoperability. In *Proceedings of the National Center for Geographic Information and Analysis Specialist Meeting on the Spatial Web*, Santa Barbara, California

Software Engineering Institute 2007 Carnegie-Mellon University Software Engineering Institute (CMU-SEI) Online Interoperability Guide. WWW document, http://www.sei.cmu.edu/isis/guide/isis-guide.htm

Stroetmann K 2005 Towards an Interoperability framework for European e-Health Research area. Brussels, Feb. 14–15, 2005. WWW document, http://www.i2-health.org/i2-h-presentations/WHO-WS_Semantic-IOP_KAS_2005-02-14.pdf

Taylor A 2004 *The Organization of Information* (Second Edition). Westport, CN, Libraries Unlimited

Tolk A 2003 Beyond technical interoperability: Introducing a reference model for measures of merit for coalition interoperability. In *Proceedings of the Eighth International Command and Control Technology Symposium (ICCRTS)*, Washington, DC

Tolk A and Muguira K 2003 The Levels of Conceptual Interoperability Model (LCIM). In *Proceedings of the 2003 Fall Simulation Interoperability Workshop*, Orlando, Florida

Turnitsa C and Tolk A 2006 Battle management language: A triangle with five sides. In *Proceedings of the Simulation Interoperability Standards Organization Spring Simulation Interoperability Workshop*, Huntsville, Alabama

Williamson I, Rajabifard A and Feeney M 2003 *Developing Spatial Data Infrastructures: From Concept to Reality*. London, Taylor and Francis

Woodley M 2004 Dublin Core Metadata Initiative. WWW document, http://dublincore.org/documents/usageguide/glossary.shtml

Yilmaz L and Tolk A 2006 Engineering ab initio dynamic interoperability and composability via agent-mediated introspective simulation. In *Proceedings of the Thirty-eighth Winter Simulation Conference*, Monterey, California: 1075–82