An Interoperable Spatio-Temporal Model for Archaeological Data Based on ISO Standard 19100

SARA MIGLIORINI, University of Verona (Italy)
PIERGIOVANNA GROSSI, University of Verona (Italy)
ALBERTO BELUSSI, University of Verona (Italy)

Archaeological data are characterized by both spatial and temporal dimensions that are often related to each other and are of particular interest during the interpretation process. For this reason, several attempts have been performed in recent years in order to develop a GIS tailored for archaeological data. However, despite the increasing use of information technologies in the archaeological domain, the actual situation is that any agency or research group independently develops its own local database and management application which is isolated from the others. Conversely, the sharing of information and the cooperation between different archaeological agencies or research groups can be particularly useful in order to support the interpretation process by using data discovered in similar situations w.r.t. spatio-temporal or thematic aspects. In the geographical domain, the INSPIRE initiative of European Union tries to support the development of a Spatial Data Infrastructure (SDI) through which several organizations, like public bodies or private companies, with overlapping goals can share data, resources, tools and competencies in an effective way.

The aim of this paper is to lay the basis for the development of an Archaeological SDI starting from the experience acquired during the collaboration among several Italian organizations. In particular, the paper proposes a spatio-temporal conceptual model for archaeological data based on the ISO Standards of the 19100 family and promotes the use of the GeoUML methodology in order to put into practice such interoperability. The GeoUML methodology and tools have been enhanced in order to suite the archaeological domain and to automatically produce several useful documents, configuration files and codebase starting from the conceptual specification. The applicability of the spatio-temporal conceptual model and the usefulness of the produced tools have been tested in three different Italian contexts: Rome, Verona and Isola della Scala.

Categories and Subject Descriptors: D.2.12 [**Interoperability**]: Distributed objects

General Terms: Design, Standardization

Additional Key Words and Phrases: Spatio-temporal model, archaeological data, interoperability

ACM Reference Format:
Sara Migliorini, Piergiovanna Grossi, Alberto Belussi, 2016. An Interoperable Spatio-Temporal Model for Archaeological Data based on ISO Standard 19100. *ACM* 0, 0, Article 0 (0), 30 pages.
`DOI`:http://dx.doi.org/10.1145/0000000.0000000

1. INTRODUCTION

In recent years, there is an increasing interest in managing archaeological data through Geographical Information Systems (GISs), since one of their main characteristics is an absolute or relative location in 3D space. This type of information, concerning the discovery of object location, allows one to derive important spatial relations

---

Author's addresses: S. Migliorini, Computer Science Department, University of Verona, Strada Le Grazie, 15, 37134 Verona (Italy); P. Grossi, Department of Cultural Studies, University of Verona, Viale dell'Università 4, 37129 Verona (Italy); A. Belussi, Computer Science Department, University of Verona, Strada Le Grazie, 15, 37134 Verona (Italy).

`DOI`:http://dx.doi.org/10.1145/0000000.0000000

between findings of a specific survey or even of different surveys. This approach is the basis of the well-known stratigraphic analysis, which is one of the main tools adopted by archaeologists during the dating process [Harris 1989]. Besides to the spatial location, also the temporal dimension is of considerable interest in the archaeological domain, and the two dimensions are often related to each other. For this reason, some attempts can be found in literature which aim to define a 4D GIS tailored for archaeological data [De Roo et al. 2014b], where the three spatial dimensions are enhanced with temporal aspects representing the fourth dimension in data analysis.

However, despite the increasing use of information technologies in the archaeological domain, the actual situation is that any agency or research group independently develops its own local database and management application which is isolated from each other, producing a fragmented accumulation of data as discussed in [Richards et al. 2013]. For instance, among the most known Italian projects we can cite: the Mappa project [Anichini et al. 2011], focused on the city of Pisa, RAPTOR [Frassine and Naponiello 2012], developed for internal use by the archaeological regional agencies of Friuli Venezia Giulia, Veneto and Lombardia, the SITAR project [Serlorenzi 2010] which collects data about the archaeological heritage of Rome, and ArcheoFI [Scampoli et al. 2013], which is focused on the city of Florence.

Conversely, the sharing of information and the cooperation between different archaeological agencies can be useful in order to preserve data and support the interpretation process by using information discovered in similar situation w.r.t. spatial-temporal or thematic aspects. For instance, the sharing of the same vocabulary for defining objects and time span allows the comparison between artifacts of the same category although distributed on areas away from each other and highlights differences or similarities between cities, suburbs and colonies during the same time span. Information that provides evidence for and helps in defining an archaeological site or historical building is an essential document that helps inform further researches. Moreover, much of archaeological results come from the destruction of primary evidence, making access to data extremely critical in order to test, reanalyse and reinterpret both data and hypothesis arising from them.

In the geographical domain, the term *Spatial Data Infrastructure* (SDI) is used to denote a technological infrastructure through which several organizations with overlapping goals can share data, resources, tools, and competencies in an effective way. In Europe, the development of a global SDI is driven by the INSPIRE project [European Commission 2007] that has been translated into an European directive. Annex I Protected Sites theme of INSPIRE Data Specifications can be considered a first attempt to treat historical and cultural heritage data inside such directive. However, it seems to be not enough, as it was highlighted in [McKeague et al. 2012], which explores aspects regarding the locations of archaeological sites and monuments, as well as the information that helps define such locations.

With the aim to lay the basis for the development of an Italian archaeological SDI, in 2011 a collaboration was started, and in 2013 formally established, between the University of Verona, in a close collaboration with the Superintendence for Archaeological Heritage of Veneto region, and the Archaeological Special Superintendence of Rome, for the definition and adoption of a common spatio-temporal model for archaeological data. Since then, a deep study was started in order to define a model which could be suitable for uniformly representing archival documents (reports, plans, drawings, photographs and other materials), excavations processes and other archaeological researches (field surveys, geophysical prospections, etc.), archaeological findings and remains, spatial and temporal features [Basso et al. 2013; Belussi et al. 2015; Bruno et al. 2015]. This model should be generic enough to be applicable in different contexts, from large metropolis characterized by many large monuments, to small cities with few large monuments and many small findings.

The aim of this paper is to define a spatio-temporal model for archaeological data based on the ISO Standard 19107 and 19108 which describe the spatial and temporal characteristics of geographical features, respectively. In order to do so, the GeoUML Methodology [Belussi et al. 2006] and Tools [Pelagatti et al. 2009] has been applied, since they are based on such standards and provide many advantages during the transition from the conceptual model to its implementation in real systems. The use of these methodology promotes the discussion and sharing between the domain experts which can abstract from technical details and focus on the semantics of data. The conceptual specification produced by the tools can be intended as a formal documentation of a dataset content and structure. Moreover, in order to promote the interoperability between different archaeological agencies or research groups, the GeoUML tools have been enhanced for automatically generating a set of additional outputs starting from the conceptual specification. These extensions have been implemented in additional plug-ins of the GeoUML Catalogue; in particular, they regards: the automatic configuration of Web Feature Services (WFSs) [ISO 2010a], the translation of query defined at conceptual level to WFS filters [ISO 2010b], the production of standard metadata describing the dataset content and structure, and the definition of an innovative way to build WebGIS applications, which is based on the concept of object navigation instead of layer displaying. These plug-ins will be presented at the end of the paper, where some examples of their usefulness will be described.

The proposed framework has been tested on three different contexts: the archaeological data of Rome, Verona and Isola della Scala, a small town in Northern Italy, which present some historical similarities but also differ widely from each other. The first one was the most important town of the ancient roman world, the second one was an important city of Northern Italy, a territory subject to the romanization process between III and I century b.C., while the third one was a small rural village (*vicus*) concerned by the romanization of northern Italy, like Verona, but without the context of a big town. The aim was to test the applicability of the model in any context and show how the sharing of information between different agencies can improve the archaeological process. In particular, in the three centers several common findings have been catalogued, such as: tombs, roads and milestones. The use of the proposed model and interoperability tools has made possible to compare many useful information, such as the construction techniques used to build the roman roads, the type of burials, the texts of the milestones, and so on.

The remainder of this paper is organized as follows: Section 2 presents several related contributions about the modeling and management of archaeological data, Section 3 briefly introduces the ISO Standard 19107 and 19108 for the representation of spatial and temporal characteristics of geographical feature. Section 4 describes the Spatio-Temporal Archaeological (*Star*) model while Section 5 illustrates how interoperability can be achieved using the *Star* model and the GeoUML tools. Finally, Section 6 summarizes the obtained results and proposes some possible future work.

2. RELATED WORK

This section presents some relevant works about the modeling and managing of archaeological data. It has been divided into two subsections, the first one describing works related to spatio-temporal modeling and the second one presenting project related to operational uses of models and infrastructures.

Modeling of archaeological data. The need for a spatio-temporal model suitable for describing archaeological data is widely recognized in literature. Several years ago, in

[Wheatley and Gillings 2002] the authors study the application of GIS and its related spatial technologies, such as the Digital Elevation Model (DEM), to the archaeological context. They conclude that these technologies have a new powerful role in archaeology, since they can facilitate the archaeological analysis and interpretation. However, the authors also state the need for a temporal GIS, namely the need to incorporate the temporal dimension during the construction of a GIS representation of data. The *Star* model includes a set of spatial primitives, such as altimetric points, which allow in some extent to reconstruct a 3D representation of the archaeological scene.

The idea to develop a comprehensive 4D GIS tailored to archaeology, where the fourth dimension is the temporal one, is also discussed in [De Roo et al. 2014a]. In particular, the authors propose a methodological framework for the development of such 4D archaeological GIS which is centered on the usability of the system and on the ability to analyse data based on archaeological investigations. In [Katsianis et al. 2008] the authors identify six potential time categories for archaeological finds which includes: excavation time, database time, stratigraphic time, archaeological time, site phase time and absolute time. The *Star* model defined in this paper includes many of these time categories. In particular, it includes the excavation time, the stratigraphic time (in terms of relative temporal positions between finds), the archaeological time (e.g. Roman Time or Middle Age), the site phase time (i.e. the distinction of different phases during an object life), and the absolute time.

In literature, the term archaeological relation usually denotes the position in space, and by implication in time, of an object or context with respect to another one [Harris 1989]. This kind of relationships is originated from stratigraphy, the main idea is that the spatial relationships that can be determined by observing deposit in section from above, represent the chronological order of their creation. Using such observation it is possible to build a matrix, called Harris matrix, where three relations are possible: unlinked or no physical relationship, later/earlier than or superposition, and equivalence. The Harris matrix is an effective method used by archaeologists in order to determine the stratigraphic relationships between contexts. In other words, the position in the matrix determine the position of the contexts in the time sequence. The *Star* model presents a set of primitives for defining stratigraphic relations between objects.

A first investigation about the applicability of ISO Standard 19108 for the representation of archaeological data is proposed in [De Roo et al. 2014b]. The authors conclude that the Standard can be successfully applied in this context, but they also highlight the lack of constructs for describing the inherent vagueness of such data. The problem of dealing with imperfection and incompleteness in archaeological knowledge was investigated also in [De Runz and Desjardin 2010] where the authors propose a way to integrate them from the modeling of data to its graphical visualization. Similarly, the Geomatics Unit of the University of Liège works from several years on the development of a conceptual data model based on the general characteristics of archaeological data, namely its spatio-temporal, heterogeneous, multimodal and imperfect character. In [Van Ruymbeke et al. 2015] the authors propose a way to integrate archaeological data ambiguity in this model. The imprecision characterizing the archaeological excavation data is treated also in [Zoghlami et al. 2012], where the author propose an approach for dealing with such imperfection during modeling and querying which is based on the use of fuzzy set theory. In [Belussi and Migliorini 2014] the authors propose an extension of the ISO Standard 19108 with fuzzy constructs, in order to incorporate the inherent uncertainty of archaeological time. Moreover, they investigate the applicability of currently available automatic techniques for time reasoning to derive new temporal knowledge or reduce the uncertainty of some dates, and in general to guide the dating process. In [Belussi and Migliorini 2017] the authors extend the model to derive temporal knowledge starting from available spatial and stratigraphic information. Such works lay the basis for the development of the *Star* model.

In general, the use of computational intelligence techniques in archaeology is discussed in [Barceló 2010], where the author analyses if it is possible to automate the archaeological knowledge production, coining the term *computable archaeology*. His conclusion is that bringing artificial intelligence into archaeology introduces new conceptual resources for dealing with the structure and growth of scientific knowledge, thus it provides an invaluable tool for archaeologists in improving their work.

CIDOC CRM [ICOM/CIDOC CRM Special Interest Group 2016] provides definitions and a formal structure for describing the implicit and explicit concepts and relationships used in cultural heritage documentation. The CIDOC CRM tries to provide a common and extensible semantic framework that any cultural heritage information can be mapped to. CIDOC CRM$_{archaeo}$ [Felicetti et al. 2016] is an extension of CIDOC CRM to support archaeological excavation processes. It has been developed and proposed during the ARIADNE project [European Commission 2016]. The main aim is to maximize interpretation capabilities after an excavation or to compare different excavations and collective studies on the same site; this can be useful also for deciding whether to continue or not the excavation activities. The ARIADNE project (Advanced Research Infrastructure for Archaeological Dataset Networking) wants to bring together and integrate existing research data infrastructures. It will enable trans-national access to research data entries and the creation of new web-based services of data repositories. Regarding to the CIDOC CRM model and for the purposes of increasing interoperability, an additional work is started, in the context of ARIADNE, in oder to define a set of rules for translating the content of the *Star* model into the CIDOC CRM classes, taking into account also the CIDOC CRM$_{archaeo}$ extension.

In [Snow et al. 2006] the authors discuss the problems that discourage the diffusion of archaeological data, making them “obscurely archived and difficult to access”. In particular, they mention not only the difficulties coming from the obscure way they are collected, but also the fact that access and policy regarding confidentiality vary considerably from one country to another. In such context, recent developments in computer and information science provide the computational tools, protocols, and standards that can help devise an integrated infrastructure.

Projects for managing archaeological data. The need of common models assumes that several sources of archaeological data are available. Archaeological Data Service (ADS) [Richards 2008] is the longest standing digital archive for archaeology. The Joint Information Systems Committee and the Arts and Humanities Research Board (now Council) provided the funding for the ADS through the Arts and Humanities Data Service (AHDS) which was established in 1996 at University of York. Its aim is to collect, describe, catalog, preserve and provide user support for digital resources that are created as a product of archaeological research. Moreover, it also has a responsibility for promoting standards and guidelines for the creation, description, preservation and use of archaeological information. Similarly, Arches [Getty Conservation Institute and World Monuments Fund 2016] is an open source, geo-spatially enabled, data management platform for cultural heritage. It was developed in conjunction with the Getty Conservation Institute and the World Monument Fund. It includes a robust module for the thesauri/terminology management which facilitates entry and retrieval of multi-language context. The use of common vocabularies can allow to discover previously unknown connections. For this reason, an additional work has been started in order to translate the vocabularies of the three case studies of this paper into the Getty Art & Architecture Thesaurus.

In [Ross et al. 2015] the authors promote the use of open-source tools during the development of a software for archaeologists, since they can encourage the reuse, sharing and dissemination of data. In particular, they summarize the experience acquired by the Federated Archaeological Information Management System (FAIMS) project. The purpose of the project was to develop a set of mobile and web applications for the creation, refinement, archiving, and dissemination of digital data. The three case studies presented in this paper are based on open-source software, which has allowed the sharing and reuse of software developed in the three realities.

Another important aspect that can increase the cooperation is the documentation of the archaeological process. In [De Roo et al. 2016] the authors analyze the general workflow of archaeological activities considering the Flemish archaeological context. In particular, they study business processes and information flows in order to determine how information is managed in an archaeological process. They identify three types of processes: archaeological fieldwork due to a planning permit, fieldwork resulting from a purely scientific question, and the preservation, conservation and publication of archaeological findings. In this context, it is of particular interest the work of the Archol – Archaeological Unit [Leiden University 2016]. Archol is a research center born in 1996 at Leiden (Netherlands), which provides a wide range of specialist for supporting the archaeological process. It has carried out several projects covering a broad spectrum of archaeological activities varying from desk-based assessments to large excavations. In *Star* the archaeological processes are considered as possible information sources for the collected archaeological data, since the aim is to store the results produced by these processes rather than supporting them during their life.

3. BACKGROUND

The aim of this section is to provide a brief introduction to the ISO Standards 19107 and 19018 for the representation of spatio-temporal data. In particular, it presents only the spatial and temporal data types used in the remainder of the paper, while for a deep understanding of the types proposed by the standards the reader can refer to [ISO 2003] and [ISO 2002], respectively.

3.1. ISO Standard 19107 for Spatial Data Representation

ISO Standard 19107 [ISO 2003] provides a conceptual schema for describing the spatial characteristics of geographical features. A *geographical feature* is an abstraction of a real world phenomenon which is associated to a location on the Earth surface.

In the model provided by the standard, spatial characteristics are described by one or more spatial attributes whose value is given by a geometric object (`GM_Object`) or a topological object (`TP_Object`). Geometry provides a quantitative description of spatial characteristics through coordinates and mathematical functions; for instance, geometries describe the shape, dimension, position and orientation of geographical features. Conversely, topology deals with the characteristics of geometric shapes that remain invariant if the space is deformed elastically or continuously; for instance, when geographical data is transformed from one coordinate reference system to another one. It is usually applied to represent objects and their spatial properties without providing any details about their location and extent. Geometric and topological primitives can be bound together or not, allowing to represent a completely abstract topological network of objects, or a partially/completely realized network, where topological primitives are associated with a geometry describing their exact shape, extent and location on the Earth surface. Figure 1 contains an extract of packages `Geometry` and `Topology` of ISO Standard 19107, it omits many parts that are not used in the paper.

`GM_Object` is the root class of the geometric type taxonomy and each one of its instances can be represented as a set of positions in a particular coordinate reference sys-

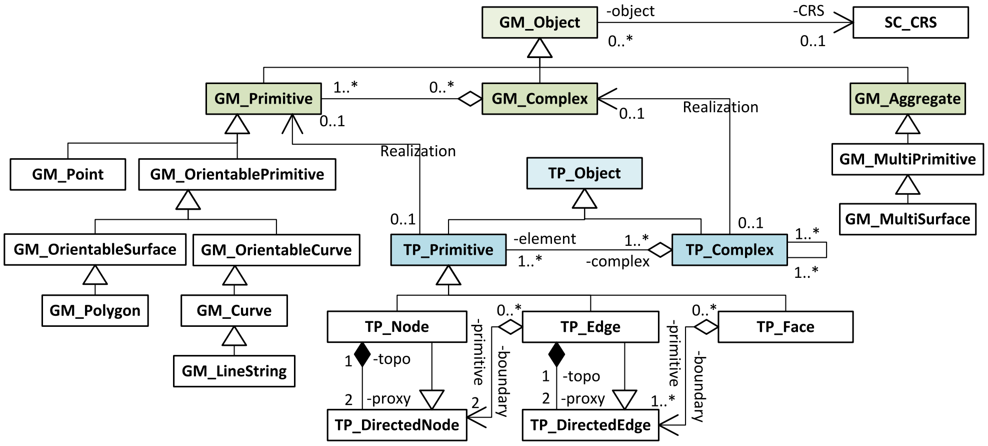


Fig. 1. Extract of the packages `Geometry` and `Topology` of the ISO Standard 19107.

tem (`SC_CRS`). It has three main directed subclasses: `GM_Primitive`, `GM_Aggregate` and `GM_Complex`, where the last one has a more elaborate internal structure than simple aggregates. The *Star* model uses only the types `GM_Point`, `GM_LineString`, `GM_Polygon` and `GM_MultiSurface`. Similarly, a `TP_Object` is the root class for topological primitives and complexes. `TP_Primitives` are the non-decomposed elements of a topological complex whose structure qualitatively describes a spatial scene.

Topological relations are used to define the relations among objects, regardless which form of representation has been chosen for them (geometrical, topological or both). The topological relation existing between two geographical features a and b is defined in the Standard according to the Dimensionally Extended 9-Intersection Model (DE-9IM) [Egenhofer and Franzosa 1991] by testing the intersection between their interior, boundary and exterior. Based on the DE-9IM, a set of seven named topological relations has been defined in [Clementini et al. 1993; Clementini and Di Felice 1995; 1996]: {*Equals* (EQ), *Disjoint* (DT), *Touches* (TC), *Crosses* (CR), *Within* (IN), *Contains* (CT), *Overlaps* (OV)}; these relations can be determined by means of the $cRelate()$ method provided by the ISO Standard 19107.

3.2. ISO Standard 19108 for Temporal Data Representation

ISO Standard 19108 [ISO 2002] describes the temporal characteristics of geographical information. The schema consists of two packages: `TemporalObjects` and `TemporalReferenceSystem`. Package `TemporalObjects` defines temporal geometric and topological primitives that shall be used as values for the temporal characteristics of geographical features. Such primitives are relative to a temporal reference system described using the package `TemporalReferenceSystem`.

Figure 2 shows an extract of the two packages containing only the classes of interest for the remainder of the paper. Concerning to the package `TemporalObject`, it includes primitive and complex objects: `TM_Primitive` is an abstract class that represents a non-decomposable element of time geometry (`TM_GeometricPrimitive`) or topology (`TM_TopologicalPrimitive`), while `TM_TopologicalComplex` is an aggregation of connected `TM_TopologicalPrimitives`. Similarly to the corresponding spatial concepts, `TM_GeometricPrimitive` provides information about temporal positions, while `TM_TopologicalPrimitive` provides information about connectivity in time.

In the temporal context there are two geometric primitives: *instant* (`TM_Instant`) and *period* (`TM_Period`), and two corresponding topological primitives: *node* (`TM_Node`) which

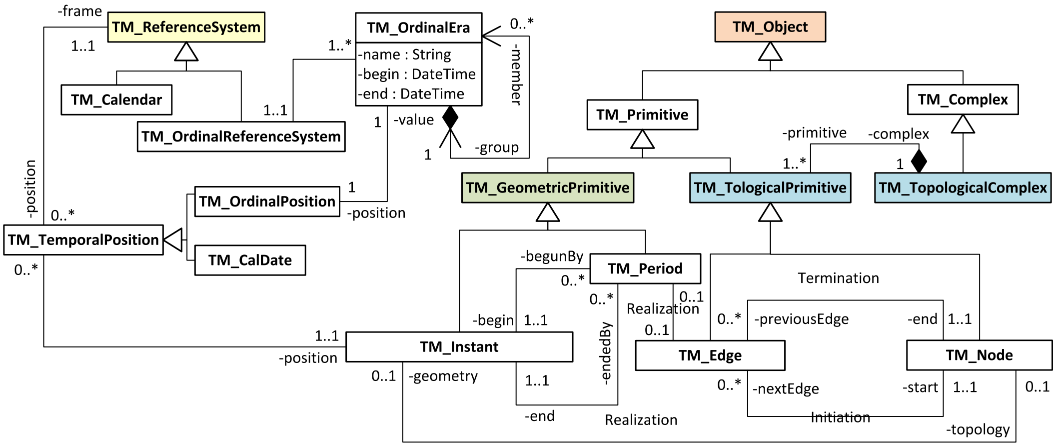


Fig. 2. Extract of the packages `TemporalObject` and `TemporalReferenceSystem` of the ISO Standard 19108.

can be realized as an instant, and *edge* (`TM_Edge`) which can be realized as a period. When a node has a realization as an instant, its temporal position is determined, otherwise it can be qualitative described by means of the temporal relations represented by the edges that start and end in the node. A similar consideration holds for edges, when they are not realized, they simply represent a temporal relation between two nodes and their corresponding period is only qualitative described. A `TM_TopologicalComplex` is a set of connected primitives. It can be represented as a graph to compactly describe relations among objects. In particular, the temporal relations considered by the standard are the Allen's ones [Allen 1983]: {*before*, *after*, *meets*, *metBy*, *overlaps*, *overlappedBy*, *finishes*, *finishedBy*, *contains*, *during*, *starts*, *startedBy*, *equals*}.

As regards to the possible kinds of temporal positions, the remainder of the paper considers only the following ones: `TM_CalDate` and `TM_OrdinalPosition`. A `TM_CalDate` is defined with relation to a `TM_Calendar`, which is discrete temporal reference system for defining temporal positions with a resolution up to one day. Conversely, a `TM_OrdinalPosition` is defined using a `TM_OrdinalReferenceSystem` which is an ordered series of events consisting of a set of `TM_OrdinalEras` that are hierarchically structured. This reference system is particularly appropriate in a number of applications of geographical information (e.g., geology and archaeology) in which relative position in time is known more precisely than duration. In such applications, the order of events in time can be well established, but the magnitude of the intervals between them cannot be accurately determined.

4. A SPATIO-TEMPORAL MODEL FOR ARCHAEOLOGICAL DATA

The *Star* (Spatio-Temporal Archaeological) model has been developed in order to consistently collect, record and process archival documents (reports, plans, drawings, photographs and other materials), excavations processes and other archaeological researches (field surveys, geophysical prospections, etc.), archaeological findings and remains. In particular, information can come from both the archives of an archaeological agency and from data recorded in publications, manuscripts and maps. The *Star* model includes three main objects of interest: `ST_InformationSource` (IS), `ST_ArchaeoPart` (AP) and `ST_ArchaeoUnit` (AU), which are characterized by some spatial and temporal dimensions described in the following.

An `ST_ArchaeoUnit` is a class of objects representing any archaeological complex or monument obtained from an interpretation process performed by the responsible offi-

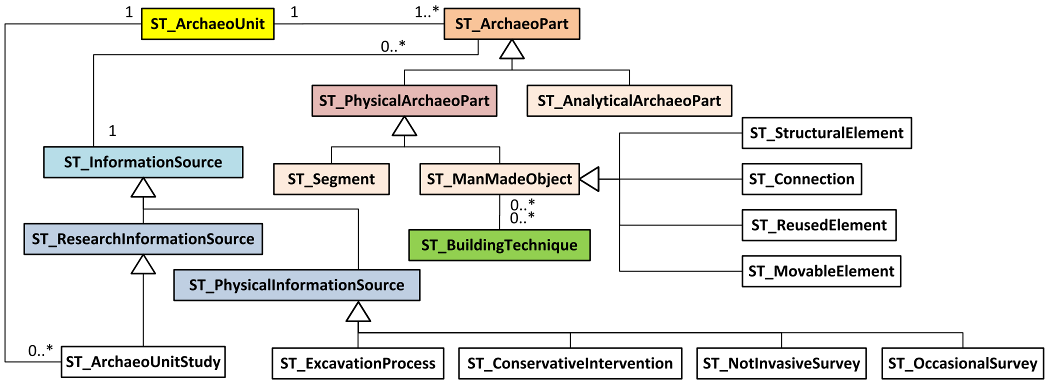


Fig. 3. Main objects of the *Star* model.

cer. Such an interpretation is carried out based on some findings, represented by `ST_ArchaeoPart` instances, retrieved during an excavation process, or a bibliographical analysis or other investigation process, described by an instance of `ST_InformationSource`. Conventionally, an archaeological unit is identified by the logical union of many archaeological partitions, which can be analyzed together producing an unambiguous archaeological monumental context (e.g. a specific ancient building).

An `ST_ArchaeoPart` concerns the scientific description of each archaeological finding of structural or non-structural nature, provided that it has an information value in ancient topography terms. Clearly, this concept is very wide and flexible and can be used to describe observations at different levels of refinement: the same object can be preliminarily described as a generic segment of matter and subsequently redefined using one of the more specific class in the hierarchy. In particular, several subclasses of the general concept have been identified in the *Star* model, as illustrated in Figure 3. The main distinction is between `ST_PhysicalArchaeoPart` and `ST_AnalyticalArchaeoPart`: physical archaeological partitions describe findings that derive from a physical observation and hence have a structural nature, in contrast with analytical archaeological partitions which represent a reconstruction hypothesis or other piece of information produced by an interpretation process. Given such classification, physical AP can be further classified in `ST_Segment` or `ST_ManMadeObject`, where a segment identifies a piece of matter representing a fragment of knowledge not yet further studied, while a man-made object represents some type of artifact or part of it, such as a structural element, a connection, a reused element or a movable element. Some of these artifacts can be also characterized by one or more building techniques.

An `ST_InformationSource` represents the way used to start collecting information about an archaeological partition or an archaeological unit. In particular, an information source can be a physically located information source, such as an excavation process, a conservative intervention, a not invasive or an occasional survey on the territory; or alternatively it can be a research or preliminary study performed on bibliographic or archival material, a particular kind of research information source is the monographic study of an archaeological unit. In terms of attribute characterization, the main difference between a physically located information source and a research information source resides on their spatial components. In case of a physically located information source, there is only one geometric attribute of interest: the territory subject of the investigation. Conversely, in case of a research information source besides to the territory interested by the study or analysis, it can be of interest also the current position of the bibliography or archival material used in the study; for instance, in case of an ancient book or an archival dossier.

Figure 3 illustrates the relation existing between the three main classes of the model. The following sections describe the spatial and temporal characteristics of these objects using the primitives introduced in the previous section. Some constraints are mentioned during the definition of such characteristics, a formal specification for them can be found in [Belussi and Migliorini 2017].

4.1. Spatial Primitives

As stated above, each main class of the *Star* model is characterized by one or more geographical properties which determine its location and extent. In particular, the spatial characteristics described in the *Star* model are summarized in Figure 4.

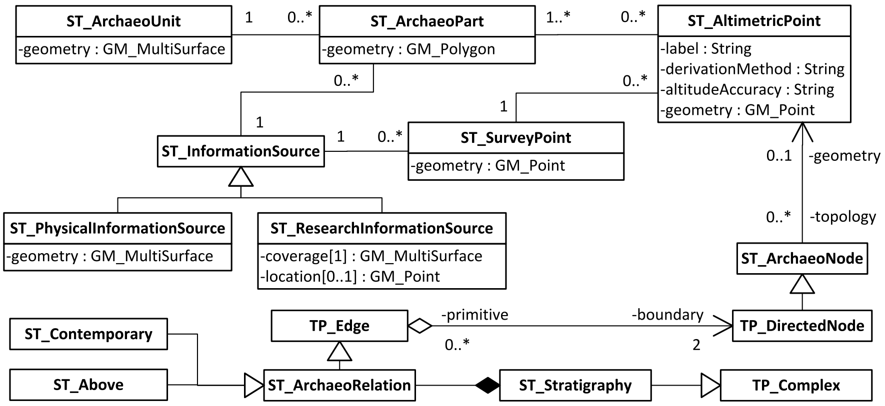


Fig. 4. Spatial components provided by the *Star* model.

The extent of an `ST_ArchaeoUnit` is represented by the property, named `geometry`, of type `GM_MultiSurface`. Each `ST_ArchaeoUnit` is connected to one or more `ST_ArchaeoPart` instances (i.e., its components) which have also a spatial attribute, named `geometry`, of type `GM_Polygon` representing their extent. Notice that the geometric components defined by the *Star* model have the main purpose to unambiguously locate the objects on the Earth surface and not to perform detailed 3D reconstructions of the objects. Clearly, the model can be extended in future to achieve also this purpose. Moreover, since archaeological partitions have the characteristics to be uniform w.r.t. to space and time attribute, they are characterized by a single polygon geometry, in fact in case of no contiguous objects, many partitions will be instantiated in order to better support the interpretation performed during the definition of archaeological units.

A containment relation exists between the extent of an archaeological partition and the extent of its corresponding unit: given an archaeological partition p and the set of its related archaeological units U, the polygon p.`geometry` representing the extent of p has to be contained inside the extent u.`geometry` of every unit $u \in U$ (*Constraint Au-Ap Containment*). Moreover, thanks to the presence of the `ST_AnalyticalArchaeoPart`, which can represent for instance a reconstruction hypothesis, given an archaeological unit u and the set of its component archaeological partitions P, the multi-surface u.`geometry` representing the extent of u has to be geometrically equal to the union of the extent of the partitions in P. In other words, a spatial part-whole relation exists between u.`geometry` and the geometric union of p_i.`geometry` for all $p_i \in P$ *(Constraint Ap-Au Part-Whole)*.

Each `ST_ArchaeoPart` may also be connected with a set of `ST_AltimetricPoints`, which represent meaningful reference points for the object. In particular, two properties are of major interest: `geometry`, a 3D `GM_Point` representing its position, and `altitudeAccuracy` which defines the degree of reliability of the z value. Given an archaeological partition p and any of its related altimetric points A, the 2D projection of the location of $a_i \in A$ has to be geometrically contained into the polygon p.`geometry` (*Ap-At Containment*).

As explained in Section 3.1, topology can be used to represent spatial associations between objects without explicitly define their geometric component. This mechanism can be particularly useful in archaeology, in order to represent the stratigraphic relation existing between some findings when their geometry is not known; for instance, because it is derived from ancient or partial studies. For this purpose, a topological complex is defined, called `ST_Stratigraphy`, which is composed of a set of `ST_ArchaeoRelations`. An archaeological relation is an abstract specialization of `TP_Edge` which can be instantiated as a `ST_Contemporary` or `ST_Above` object, in order to represent a *contemporary with* or *above* stratigraphic relation, respectively. Notice that the *below* relation can be obtained using an *above* one and swapping the start and end nodes. Each archaeological relation connects two nodes which are represented by the `ST_ArchaeoPoint` class and can be realized as `ST_AltimetricPoints`, as in Figure 4.

The spatial component of an `ST_InformationSource` depends upon its type. In particular, given the two main kind of information source: `ST_PhysicalInformationSource` and `ST_ResearchInformationSource`. The first one represents a physically located information source which is characterized by an extent of type `GM_MultiSurface`, while the second one denotes a research or preliminary study performed on bibliographic or archival material which has two spatial components of interest: an optional `GM_Point` representing the current location of the bibliographic or archival material when relevant (for example, when ancient sources are considered), and a `GM_MultiSurface` representing the territory treated/analysed by the research. Notice that given an archaeological partition p and its related information source i, the location of p has to be geometrically contained into the polygon representing the extent of i, if i represents a physically located source, or into the polygon representing the coverage of i, if i represents a research study (*Is-Ap Containment*).

Each `ST_InformationSource` is also connected to a set of `ST_SurveyPoints` which are certified reference points located inside the excavation or the coverage area. They are used to define the altitude of the related `ST_AltimetricPoints`, since its z component is given relative to a particular survey point. Given an information source s and the set of its survey points P, the 2D projection of the location of each $p \in P$ has to be geometrically contained into the polygon representing the extent of s, if s represents a physically located source, or into the polygon representing the coverage of s, if s represents a research study (*Is-Sp Containment*).

4.2. Temporal Primitives

In the archaeological context, time dimension may be specified using different reference systems and different calendars. For this reason, the paper considers only `TM_TemporalPosition` objects as possible instances for `TM_Position`. In other words, it assumes that the reference system and the used calendar are always explicitly declared.

Given an `ST_ArchaeoUnit`, a set of possible temporal *phases* of its evolution are identified, then each component `ST_ArchaeoPart` is assigned to one or more of these phases, as illustrated in Figure 5. This assignment process is one of the fundamental tasks in archaeology [Katsianis et al. 2008]. For instance, examples of phases in the existence of an archaeological entity are: installation/foundation, life/use, and renovation/reuse. In *Star* the sequence of phases describing the evolution of an `ST_ArchaoeUnit` object is defined as an `ST_Sequence` object, which in turn is a composition of `ST_Phases`. Clearly, different interpretations captured by the definition of different archaeological units can lead to different sequences that make it possible to handle ambiguous hypothesis, like the concept of interpretative sequence in [Van Ruymbeke et al. 2015].

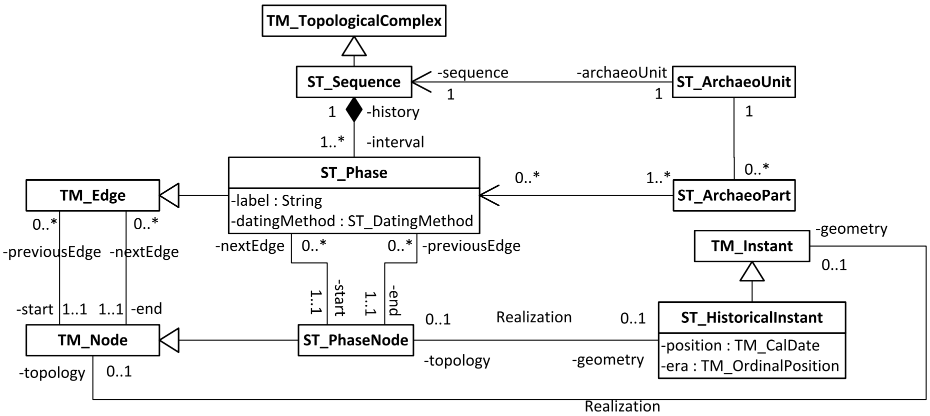


Fig. 5. Temporal aspects characterizing an archaeological unit in the *Star* model.

We can observe that, since the relative order between each pair of phases is typically known with more certainty than their absolute position, the collection of phases in the sequence of an `ST_ArchaeoUnit` can be modeled using a topological approach, as also suggested in the ISO Standard 19108 and summarized in Figure 5. More specifically, the `ST_Sequence` of an `ST_ArchaeoUnit` can be described as a topological complex, thus the `ST_Sequence` class can be declared in the model as a specialization of the `TM_TopologicalComplex` class of the standard. Moreover, an `ST_Sequence` is composed of several `ST_Phase` objects; therefore, the `ST_Phase` class has to be declared in the model as a specialization of `TM_TopologicalPrimitive` class (i.e., `TM_Edge`, since it represents a period). *Star* adds two additional properties to each edge: a meaningful label (e.g., foundation, use, etc.) and the specification of the dating method (e.g., stratigraphic analysis). Also the `Initiation` and `Termination` associations are specialized, because they connect each `ST_Phase` instance with particular nodes (instances of the class `ST_PhaseNode` specializing `TM_Node`) which can be realized with a specialization of `TM_Instant`, called `ST_HistoricalInstant`. Each `ST_HistoricalInstant` has two attributes: a `position` (inherited from `TM_Instant`), which here can be only of type `TM_CalDate`, and a new attribute, called `era`, which is a `TM_OrdinalPosition`; at least one of them has to be not null. The value of the `era` attribute is a `TM_OrdinalEra` object defined with reference to a particular `TM_OrdinalReferenceSystem`, which is called `ST_NamedYearRange` in *Star* and is exemplified in the Online Appendix. Given a `ST_HistoricalInstant` i, if its attributes `era` and `position` have been both specified, the `position` attribute has to be geometrically contained inside the `era` one (*P-E Containment*).

Each `ST_ArchaeoPart` is dated in some way and is assigned to certain phases of the associated `ST_ArchaeoUnit`. In particular, different dates can be assigned to an archaeological partition, using different roles, for instance: the establishment or origination date which represents the date of its construction by a human activity or by a physical phenomenon, respectively; the date in which its use has started, the date of its renovation or preservation, and finally the date of its destruction or end of use.

The date assigned to an `ST_ArchaeoPart` is described in the model, as illustrated in Figure 6, by the `ST_ArchaeoDate` class, which is related to the ISO Standard 19108 since it is a specialization of the `TM_Node` class and has consequently a realization as `TM_Instant`. An additional attribute describing the applied dating method characterizes the `ST_ArchaeoDate` class. Exploiting the classes of the ISO Standard 19108, the

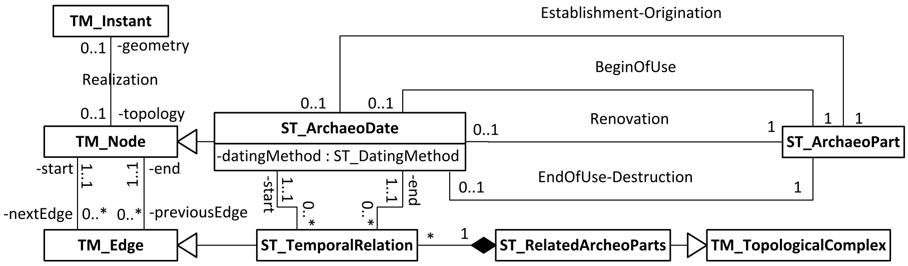


Fig. 6. Temporal aspects characterizing an archaeological partition in the *Star* model.

chronology of a partition can also be represented by topological primitives, since a relative order between related partitions is better known, than their absolute location. Some edges, called `ST_TemporalRelation`, can be placed between nodes representing `ST_ArchaeoDate` objects, in order to define temporal relations between the dates of related archaeological partitions. A set of temporal relations relative to some connected partitions constitutes a topological complex, called `ST_RelatedArchaeoParts` in Figure 6. In accordance with the standard, the relative position of two `TM_TopologicalPrimitives` depends upon the position they occupy within the sequence of primitives that makes up a `TM_TopologicalComplex`. The example in the Online Appendix illustrates a possible topological structure composed of a set of related partitions.

An implicit ordering relation exists between each possible date assigned to an archaeological partition: given a `ST_ArchaeoPart` a, a.`Establishment-Origination` $\leq_t$ a.`BeginOfUse` $\leq_t$ a.`Renovation` $\leq_t$ a.`EndOfUse-Destruction`, where the symbol $\leq_t$ denotes the disjunction between the temporal relations "before" or "equals" (*Dap Constraint*). Moreover, given a `ST_ArchaeoPart` a, each of its dates has to be contained inside one of its assigned phases p (*Map Constraint*).

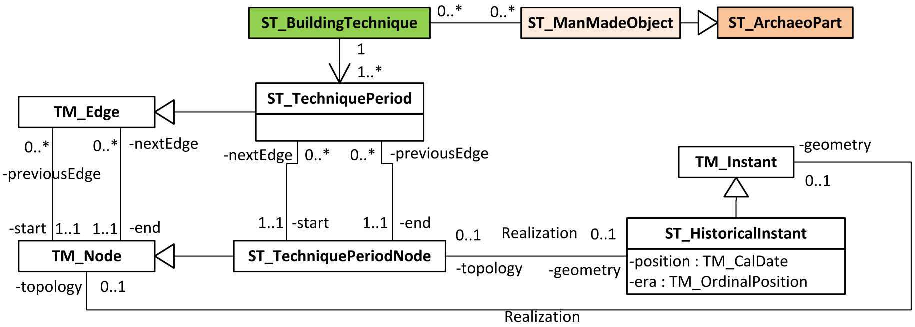


Fig. 7. Temporal aspects characterizing the building technique of an archaeological partition.

A particular kind of `ST_ArchaeoPart` is the one classified as `ST_ManMadeObject`, which is characterized by an association with zero or more `ST_BuildingTechniques`. Each building technique represents a particular technique applied during the construction process which has several attributes, including a validity period, as illustrated in Figure 7. Such period is represented by the class `ST_BuildingTechniquePeriod` which is a specialization of `TM_Edge` whose nodes, called `ST_BuildingTechniqueNode`, have a particular realization as `ST_HistoricalInstant`. This special kind of instant has been already used in the definition of archaeological unit phases.

A constraint exists between the dating characterizing the building techniques of an archaeological partition and its own dating. More specifically, given an `ST_ManMadeObject` characterized by a set of building techniques B, its `Establishment-Origination` and `Renovation` dates cannot be in contrast with the dating of B, but they have to be geometrically contained in the period assigned to one of the techniques in B (*Bt Constraint*).

Each `ST_InformationSource` is characterized by a time dimension that is represented as a geometric primitive, since it is generally known and documented in some way, as illustrated in Figure 8. This geometric primitive can be instantiated with both a `TM_Instant` or a `TM_Period` depending on the particular type of information source and the available information.

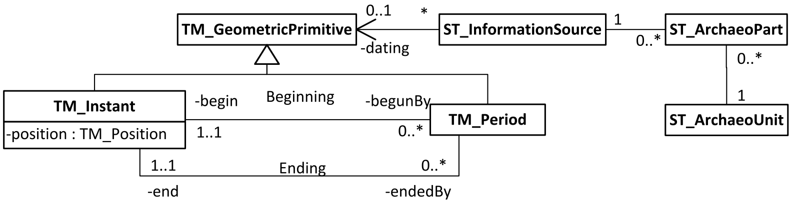


Fig. 8. Temporal aspects characterizing an information source and a document in the *Star* model.

5. FROM THE CONCEPTUAL MODEL TO INTEROPERABLE SERVICES

This section describes how the GeoUML methodology and tools can be used to support the interoperability of agencies sharing the *Star* conceptual model, namely how they can promote the construction of an archaeological SDI. Section 5.1 starts by illustrating how a conceptual specification compliant with the *Star* model can be formalized using the GeoUML tools, highlighting the benefit of such representation and the possible outcomes that can be automatically generated from such specification. Then, Section 5.2 concentrates on the possibility to share data described using the *Star* model through Standard WFSs, exploiting all its capabilities thanks to an innovative WebGIS visualization approach. Finally, Section 5.3 discusses the possibility to define conceptual interoperable queries and automatically translate them into WFS filters.

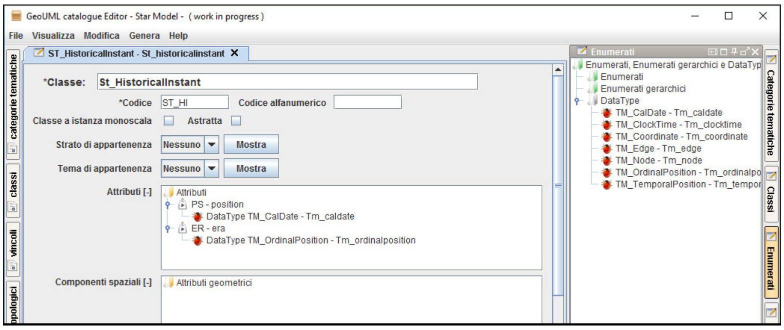
5.1. GeoUML Concetual Modeling

The GeoUML methodology [Belussi et al. 2006] and its tools [Pelagatti et al. 2009] was developed in order to: (a) support the definition of geographical conceptual schemas, (b) perform their automatic translation into a physical implementation on a given technology, producing a data product, and (c) validate the conformance of a data product to a given conceptual schema. Two main GeoUML tools are available at the web site http://spatialdbgroup.polimi.it: the *GeoUML Catalogue*, for the definition of conceptual models and the generation of their physical implementations, and the *GeoUML Validator*, for checking the conformance of a data product with respect to a conceptual schema defined by the Catalogue, for instance as regards to spatial constraints.

The principles behind the development of the methodology and its tools were to adhere to the ISO Standards 19100 whenever they apply, keeping a clear separation between the conceptual and the implementation levels. At this regards, the produced conceptual specification is independent from any specific GIS product but can be implemented using currently available technologies. The development of this approach was financed by CISIS [CISIS 2016], the coordinating authority of Italian Regions for spatial data, in order to guarantee that spatial databases created by different Regions satisfy common spatial properties. This is considered a fundamental requirement for the national SDI. The GeoUML tools have been used for the definition of the Italian National Core and for supporting the mapping of the National Core content towards the INSPIRE data specifications and the data conversion [Belussi et al. 2014].

The adoption of this approach in the specification and development of the *Star* model has produced many advantages which are described in the remainder of this section, together with the presentation of a set of implemented plug-ins.

Conceptual Model Definition. The abstraction from any specific GIS technology has promoted the collaboration between data designers and domain experts in order to describe the intrinsic properties of the archaeological information without getting lost in technical details. Previous experiences have revealed that choices on data representation are sometimes driven by technical limits or compromises, rather than by application needs. The main disadvantage in the use of the GeoUML Catalogue for the definition of the *Star* model is that it contains all spatial types of ISO Standard 19107 as primitive types, but it does not fully implement the ISO Standard 19108, for the temporal dimension. In particular, it only supports the definition of a temporal positions in terms of `Date`, `DateTime` or `Time`. However, the Catalogue allows one to specify custom `DataTypes` using available primitive types or previously defined data types and enumerations. Therefore, a set of custom data types has been created in order to represent the classes of the ISO Standard 19108 and their specialization presented in Section 4.2, as illustrated in Figure 9.


GeoUML catalogue Editor - Star Model - (work in progress)

ST_HistoricalInstant - St_historicalinstant

*Classe: St_HistoricalInstant
*Codice ST_HI
Codice alfanumerico
Classe a istanza monoscala ☐
Astratta ☐
Strato di appartenenza Nessuno
Tema di appartenenza Nessuno
Attributi [-]
- Attributi
  - PS - position
    - DataType TM_CalDate - Tm_caldate
  - ER - era
    - DataType TM_OrdinalPosition - Tm_ordinalposition

Componenti spaziali [-]
- Attributi geometrici

Enumerati
- Enumerati, Enumerati gerarchici e DataTyp
  - Enumerati
  - Enumerati gerarchici
  - DataType
    - TM_CalDate - Tm_caldate
    - TM_ClockTime - Tm_clocktime
    - TM_Coordinate - Tm_coordinate
    - TM_Edge - Tm_edge
    - TM_Node - Tm_node
    - TM_OrdinalPosition - Tm_ordinalpo
    - TM_TemporalPosition - Tm_tempor

Fig. 9. Example of definition of the *Star* temporal data type `ST_HistoricalInstant` using the GeoUML Catalogue. A set of temporal types has been defined in order to implement the ISO Standard 19108.

Given a conceptual specification, the GeoUML Catalogue automatically generates many different products that range from textual documentations to different physical implementations. In particular, it automatically generates a set of documents which contains the description of each feature class (domain object), its properties, its associations with other classes, and so on.

In order to better describe not only the structure of the model, but also the characteristics of the data that will be defined in a conceptual specification, a plug-in was developed that allows the definition of a set of metadata and produces an XML file compliant with the ISO Standard 19115 Geographic Information – Metadata. This standard provides information about the identification, the extent, the quality, the spatial and temporal schema, the spatial reference system, and the distribution of digital geographical data. For instance, it requires to specify the spatial and temporal extent of the data contained in the dataset, as exemplified in Listing 1. These metadata can be particularly useful in order to determine which datasets have sense to compare in order to improve the archaeological interpretation process. For instance, the three datasets considered in the paper are characterized by an overlapping temporal extent during which Rome was the most important town of the ancient Roman world, while the other two were subject to the romanization process between III and I century b.C..

LISTING 1: Extract of the metadata file compliant with ISO Standard 19105 containing the information about spatial and temporal extent of the dataset.

```
<?xml version="1.0" encoding="UTF-8" standalone="no"?>
<MD_Metadata ...>
  [...omissis...]
  <extent><EX_Extent><geographicElement><EX_GeographicBoundingBox>
    <westBoundLongitude><gco:Decimal>11.007623</gco:Decimal></westBoundLongitude>
    <eastBoundLongitude><gco:Decimal>10.988319</gco:Decimal></eastBoundLongitude>
    <southBoundLatitude><gco:Decimal>45.450506</gco:Decimal></southBoundLatitude>
    <northBoundLatitude><gco:Decimal>45.435433</gco:Decimal></northBoundLatitude>
  </EX_GeographicBoundingBox></geographicElement></EX_Extent></extent>
  <extent><EX_Extent><temporalElement><extent>
    <gml:timePeriod>
      <gml:beginPosition>-300</gml:beginPosition>
      <gml:endPosition>-1</gml:endPosition>
    </gml:timePeriod>
  </extent></temporalElement></EX_Extent></extent>
  [...omissis...]
</MD_Metadata>
```

Physical Implementations. Given a single conceptual specification, the GeoUML Catalogue allows one to define one or more data product specifications and for each of them to obtain the corresponding physical implementation of the model, for instance it automatically produces the SQL scripts for the database schema creation (i.e., the SQL schema is an example of physical implementation). The tools ensure the coherence preservation between the conceptual schema and its related implementations. In particular, the three applications of the *Star* model share the same conceptual schema but can be characterized by different physical implementations, i.e. you can choose between PostGIS or Oracle Spatial systems. The translation from a conceptual specification to each physical implementation requires the definition of a *data product specification* which contains several mapping information that ranges from custom choices, such as table names, to specific information that depends upon the chosen physical implementation technology, for instance the management of spatial data types.

In order to support the rapid development of management applications based on the defined conceptual model, another plug-in has been developed for automatically generating a set of Java classes with JPA (Java Persistence API) annotations [Oracle 2013] for accessing the created database. This plug-in also starts from the conceptual model and a specific data product specification, and produces a set of classes, enumerations, configuration files, converters, and so on. In particular, while the definition of temporal data types could be easily obtained using the available temporal primitives, the main difficulty was the development of a converter for geometric types which defines the correspondence between a spatial type of a database system, like PostGIS, and the one in the Java Topology Suite (JTS) library [Vivid Solutions 2003].

Besides to the SQL implementations, the GeoUML Catalogue allows one to produce an XSD representation of the model. It exposes the XML encoding of the data described in the conceptual specification by applying the encoding rules of the ISO Standard 19136 Geographic Information – Geography Markup Language (GML) Annex E. This XSD file can be also used as a starting point for configuring a Standard Web Feature Service (WFS) [ISO 2010a]. The configuration of a WFS and its use to increase the interoperability between archaeological agencies will be described in Section 5.2.

Constraint Validation. The other GeoUML tool is the Validator, which allows one to check the conformance of a dataset w.r.t. a conceptual specification, and in particular to check spatial constraints defined at conceptual level on a real database. In order to do so, it automatically translates the conceptual spatial constraints into SQL queries. For instance, this tool can be used to automatically check the spatial constraints given in Section 4. Unfortunately, it does not support the validation of temporal constraints and this can be considered as a useful future extension of the GeoUML tools together with the native support of the complex temporal data types of the ISO Standard 19108.

5.2. Data Sharing through WFS

The OGC Web Feature Service (WFS) Interface Standard [ISO 2010a] defines an interface for describing data manipulation operations on geographical features over the Web in a standard way. In particular, such operations include the ability to (1) retrieve or query features based on spatial and non-spatial conditions (filters), (2) create a new feature instance, (3) delete or update an existing feature instance.

Existing tools, such as GeoServer [OSGeo 2015], are able to automatically configure a WFS starting from an existing spatial database. The main drawback of this configuration resides on the flat nature of the obtained layers. In other words, each defined layer exposes a single table or view of the database, while any association defined at database level is generally lost. For this reason, it is common to define views that aggregate information coming from different tables, in order to obtain a minimum navigation between objects. Listing 2 illustrates an example of WFS exposing some archaeological partitions using a flat style, namely by defining a custom database view. As you can notice, the value of some properties such as the `representation_accuracy`, which comes from an enumerated domain stored into a separate table, has been di-

LISTING 2: Extract of the WFS exposing some archaeological partitions using a flat style.

```
<wfs:FeatureCollection ...>
  <geoarch_verona:st_archaeo_part_view fid="....">
    [...omissis...]
    <geoarch_verona:representation_accuracy>detailed
    </geoarch_verona:representation_accuracy>
    <geoarch_verona:bibliographies>
      C. Cipolla, "Una tomba barbarica scoperta nel Palazzo Miniscalchi a Verona"
      L. Franzoni, "Edizione archeologica della carta d'Italia al 100.000: Verona"
    </geoarch_verona:bibliographies>
    <geoarch_verona:information_source>OI-359
    </geoarch_verona:information_source>
    [...omissis...]
  </geoarch_verona:st_archaeo_part_view>
</wfs:FeatureCollection>
```

rectly reported in the view in place of its identifier contained in the original table. Even if this situation can be desirable, the major limitation regards the representation of $n - n$ associations or associations towards complex objects. The `bibliographies` property in Listing 2 is an example of $n - n$ association towards a complex object (i.e., an object with many properties). In this case, each target object has been exploded into a string and the view contains the concatenation of all exploded values. This solution is a clear limitation in the navigation possibilities offered by the association: it is not possible to reach the target object and/or to navigate back to all possible source objects that reference it. Finally, the property `information_source` represents an association in which the target is a complex object whose properties cannot be easily represented as a single string. In this case, it will be desirable to directly navigate to the object and see all its properties in a structured form.

However, the WFS capabilities allow one to overcome this problem through the use of a more complex structure where property values can be `XLinks` towards other object instances. Clearly, the definition of a WFS that directly reflects the database structure, requires a more elaborated configuration. For instance, in Degree [OSGeo 2016a] the configuration of a WFS is performed through a configuration file and several feature store configuration files, which provide access to the actual data. Clearly, the more the desired structure is articulated, the more the configuration files become complex.

LISTING 3: Extract from the XSD file produced by the GeoUML Catalogue for representing in XML an archaeological partition.

```
<complexType name="ST_ARCHAEO_PARTType">
  <complexContent><extension base="gml:AbstractFeatureType"><sequence>
    <element name="UUID" minOccurs="1" maxOccurs="1"><simpleType>
      <restriction base="string"><maxLength value="70"/></restriction>
    </simpleType></element>
    <element name="GEOMETRY" type="gml:MultiSurfacePropertyType"
             minOccurs="0" maxOccurs="1"/>
    <element name="ACCESSIBILITY_NOTE" minOccurs="0" maxOccurs="1"><simpleType>
      <restriction base="string"><maxLength value="300"/></restriction>
    </simpleType></element>
    <element name="ACQUISITION_METHODOLOGY_ID"
             type="sitar:D_ST_ACQUISITION_METHODOLOGY_EnumerationType"
             minOccurs="0" maxOccurs="1"/>
    <element name="GEOMETRY_ALTITUDE" type="double" minOccurs="0" maxOccurs="1"/>
    <element name="INFORMATION_SOURCE_ID"
             type="gml:ReferenceType" minOccurs="1" maxOccurs="1">
      <annotation><appinfo>
        <gml:targetElement>ST_INFORMATION_SOURCE</gml:targetElement>
      </appinfo></element>
    [...omissis...]
  </sequence></extension></complexContent>
</complexType>
<element type="sitar:ST_ARCHAEO_PARTType" name="ST_ARCHAEO_PART"
         substitutionGroup="gml:AbstractFeature">
```

Following the encoding rules of ISO Standard 19136 Annex E, it is possible to derive from a conceptual model written in UML, the corresponding representation in XML where all the classes, with their attributes, and all the association roles between them are preserved and explicitly represented. The XSD file describing such XML syntax can be automatically generated by a plug-in of the GeoUML Catalogue. Listing 3 shows an example of such XSD file automatically produced by the tool. Moreover, an additional plug-in has been developed, which allows to obtain also the XML file for Degree that specifies the mapping between each element contained in the XSD file and the database tables and columns that are defined in a specific physical implementation of the conceptual schema. Listing 4 shows the XML the mapping between the XML elements and the database tables and columns of a specific implementation.

LISTING 4: Extract from the XML file for configuring a Degree WFS that is produced by the GeoUML Catalogue. It maps the XML elements towards the database tables and columns.

```
<SQLFeatureStore xmlns="http://www.deegree.org/datasource/feature/sql" ...>
  <JDBCConnId>inspire</JDBCConnId>
  <StorageCRS srid="3003" >EPSG:3003</StorageCRS>
  <FeatureTypeMapping name="sitar:ST_ARCHAEO_PART" table="ST_ARCHAEO_PART">
    <FIDMapping prefix="sitar_ST_ARCHAEO_PART_">
      <Column name="classID" type="string"/>
      <UUIDGenerator />
    </FIDMapping>
    <Primitive path="star:UUID" mapping="classID"/>
    <Complex path="star:GEOMETRY"><Geometry path="." mapping="geometry"/></Complex>
    <Primitive path="sitar:ACCESSIBILITY_NOTE" mapping="accessibility_note"/>
    <Complex path="sitar:ACQUISITION_METHODOLOGY_ID">
      <Join table="ST_ACQUISITION_METHODOLOGY" fromColumns="code"
            toColumns="accessibility_methodology_id" />
      <Primitive path="text()" mapping="name"/>
    </Complex>
    <Primitive path="sitar:GEOMETRY_ALTITUDE" mapping="geometry_altitude"/>
    <Complex path="sitar:INFORMATION_SOURCE_ID"><Feature path=".">
      <Join table="sitar:ST_INFORMATION_SOURCE" fromColumns="classID"
            toColumns="information_source_id"/>
      <Href mapping="information_source_a_href"/>
    </Feature></Complex>
  </FeatureTypeMapping>
  [...omissis...]
</SQLFeatureStore>
```

Different interoperability experiments have been performed on data provided by the three agencies using the *Star* model. In particular, a first experiment has been performed using the flatten WFS structure which is based on the definition of some database views. This experiment was motivated by the aim to test interoperability possibilities and benefits. Moreover, currently available GIS tools which are compatible with the WFS Standard usually support only this kind of WFS structure. This is the case of some desktop applications, such as QGis [OSGeo 2016c], or web libraries, such as OpenLayers [OSGeo 2016b]. More specifically, three WFSs have been configured which serve the data of Rome, Verona and Isola della Scala, and some queries have been defined in order to recover similar archaeological objects in the three territories. For instance, the set of Roman roads and related milestones, or the set of tombs and necropolises dating back to the same historical period, with the final goal to investigate and highlight differences and similarities between Rome and the romanized territory of northern Italy, or between the urban context of Rome and the one of a colony (Verona) or of a rural area (Isola della Scala). This experiment highlights the potential benefits of the interoperability in terms of possible collaborations between different archaeologists which can share their information for supporting the interpretation process. In the specific case of the just mentioned queries, the road building techniques of the three territories were compared and the differences between Rome, the urban context of a colony and the extraurban context of a rural area were highlighted. Besides that, the funerary contexts of the three areas were compared highlighting and confirming already known theories; in particular, as regards to the differences between Rome and the romanized territory of northern Italy, where influences of the pre-roman period survived even after the romanization.

However, this experiment also highlights the limits due to the use of a flatten WFS structure; the inability to navigate among objects exploiting their association. This possibility should be useful both during visualization and query. Available GIS tools usually are not able to properly treat the links between objects specified in an XML document through XLink. More specifically, if an object property is a link to another object, it is not possible to directly access the other object and see its properties.

Therefore, a second experiment has been performed, which uses a complex WFS structure exploiting the XLink technology for connecting objects. This WFS has been realized in Degree using the XSD configuration file produced by the Catalogue. Moreover, we designed an innovative WebGIS interface which is able to treat such complex WFS structure. The WebGIS has been developed in the Java EE environment, using the JSF technology [Oracle 2015] and the Primefaces library, for the web interface, and exploiting the Google Maps API [Google 2016] for the map visualization and management. The use of the Google Maps API allows one easily share the same WebGIS implementation on different platforms, in particular, it can be easily integrated into an Android App, as illustrated in Figure 10.

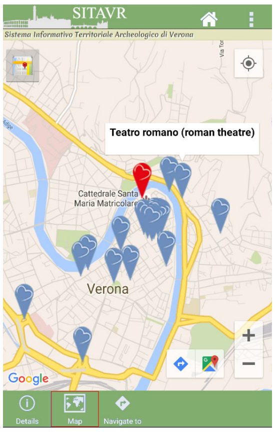


Fig. 10. Example of the WebGIS integration into an Android application.

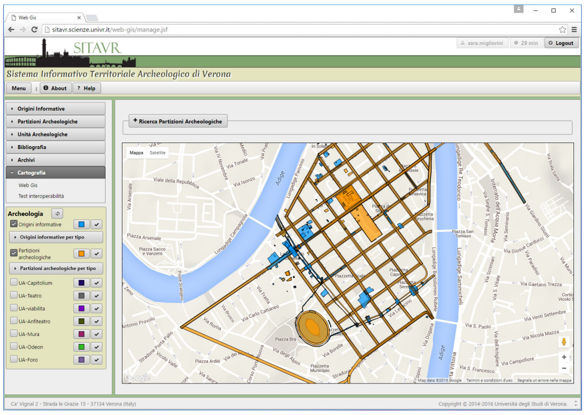
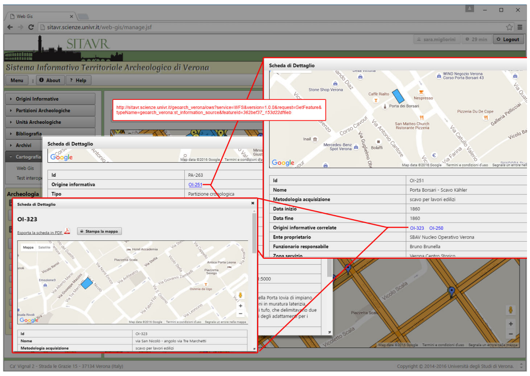


Fig. 11. Graphical interface of the WebGIS developed for performing the interoperability tests.

The WebGIS application connects to a WFS to obtain a stream of data in XML or GeoJSON format, then such stream is processed in order to build the corresponding objects to be displayed on the map. At a first glance, the GIS structure is very similar to the traditional one, because objects are organized into layers corresponding to a desired classification. For instance, the *Star* objects are classified into the three main categories: information source, archaeological partition and archaeological unit, as exemplified in the left menu of Figure 11. However, the main difference is in the management and visualization of each single object. In particular, during the displaying of an object information window, each link to another object is automatically converted into another WFS invocation which retrieves the details of that object and display it into another information window, see Figure 12. Anyway, in order to reduce the number of WFS invocations, if the linked object is simply a reference to a vocabulary term (i.e., an enumerated value), this term is automatically reported into the current window as a simple literal value, see for instance the property “Tipo” in Figure 12. Through a configuration file, it is possible to configure and translate in different languages the label that appears on the information window.


http://sitavr.scienze.univr.it/geoarch_verona/ows?service=WFS&version=1.0.0&request=GetFeature&typeName=geoarch_verona:st_information_source&featureId=362bef37_153d22df6eb

Scheda di Dettaglio

Id: PA-263
Origine informativa: OI-251
Tipo: Partizione cronologica

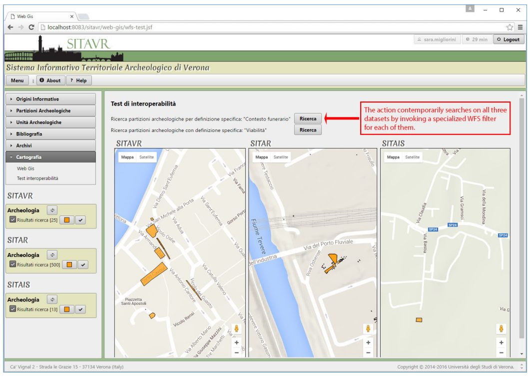
Scheda di Dettaglio

Id: OI-251
Nome: Porta Borsari - Scavo Kähler
Metodologia acquisizione: scavo per lavori edilizi
Data inizio: 1860
Data fine: 1860
Origini informative correlate: OI-323 OI-250
Ente proprietario: SBAV Nucleo Operativo Verona
Funzionario responsabile: Bruno Brunella
Zona servizio: Verona Centro Storico

Scheda di Dettaglio

OI-323

Id: OI-323
Nome: via San Nicolò - angolo via Tre Marchetti
Metodologia acquisizione: scavo per lavori edilizi


The action contemporarily searches on all three datasets by invoking a specialized WFS filter for each of them.

Test di interoperabilità

Ricerca partizioni archeologiche per definizione specifica: "Contesto funerario" Ricerca

Ricerca partizioni archeologiche con definizione specifica: "Viabilità" Ricerca

Fig. 12. Interface of the WebGIS developed for the interoperability tests: each reference to another object is a link to the corresponding information window, the reference is automatically translated into a WFS invocation which retrieves the corresponding object data.

Fig. 13. Example of instantiation of three maps displaying different *Star* datasets and of execution of the same conceptual query on them. The two buttons on the top of the page invoke the specialized WFS filters obtained by translating the conceptual query on the real structure of the three datasets.

Several instances of the map can be configured in a page for contemporarily displaying the same kind of content or perform the same queries on different datasets. For instance, this mechanism has been applied to display and query three different maps containing the data of Rome, Verona and Isola della Scala, see Figure 13. Besides to the simplest query performed by filtering on the object kind, many other interoperable queries can be defined and contemporarily performed on the three maps. This possibility will be extensively discussed in the following section.

5.3. From Conceptual Queries to WFS Filters

ISO Standard 19143 – Filter Encoding [ISO 2010b] describes an XML and KVP (key-value pairs) encoding of a system neutral syntax for defining *query expression*. Originally it was part of the OGC’s WFS Specification since it defines the way to filter WFS data instances; nowadays, it has been separated into an individual Standard because that type of filtering is not limited to the application of the ISO Standard 19142.

A *WFS query expression* is an action that performs a search over some sets of resources and returns a subset of those resources. A fundamental type of query expression is the *ad hoc query expression*, namely a query that is not known before the time it will be executed, in contrast with stored queries. An ad hoc query expression contains: the name of one or more resource types to query, an optional *projection clause* enumerating the properties to present in the response, an optional *selection clause* that constraints the properties of those resource types in order to define the result set, and an optional *sorting clause* specifying the order in which the result set is presented. The only mandatory part of a query expression is the specification of the names of the resource types to query. As regards to the various other optional clauses, for the purpose of this paper, this section concentrates only on the selection one.

The selection clause or filter contains a sequence of *predicates* or operators. Two main kinds of operators can be distinguished: `IdOperator` and `NonIdOperator`. An `IdOperator` tests whether the identifier of an object matches a specific value, conversely various `NonIdOperator` are supported, in particular: *comparison* and *logical operators*, and *spatial* or *temporal predicates*. Each operator requires to specify one or two arguments, called *expressions*, of various types: value references, literals, and functions or procedures. In particular, a value reference can be, for example, the *name of a property* of a resource or *a path expression* that represents a value that is part of the property of a resource, encoded using the XML Path Language.

An example of query defined on the archaeological partition of the *Star* model is the following one which selects all information sources of type `ST_ExcavationProcess` whose specific acquisition methodology is "`extensive excavation`":

```
<wfs:Query typeName="star:st_excavation_process" aliases="IS">
  <fes:Filter><fes:PropertyIsEqualTo>
    <fes:ValueReference>acquisition_methodology</fes:ValueReference>
    <fes:Literal>extensive excavation</ogc:Literal>
  </fes:PropertyIsEqualTo></fes:Filter></wfs:Query>
```

Notice that the mandatory name of the resource to query is given by attribute `typeName`, while the filter is contained inside the element `fes:Filter`. Such filter uses a comparison operator `fes:PropertyIsEqualTo` between a reference to the resource property `acquisition_methodology` and the literal value "`extensive excavation`".

The WebGIS application can support the user in the definition of a WFS Filter, by means of an interface for the specification of conceptual queries. In particular, in order to provide this feature, the WebGIS application can load the conceptual specification produced by the GeoUML Catalogue and allows the user to specify a conceptual query on it, abstracting from any implementation details.

A conceptual query can be defined using a syntax similar to JPQL (JPA Query Language) [Oracle 2013] which is able to traverse associations between objects and to retrieve nested properties. However, some restrictions are applied to such syntax in order to reflect the limitations of the ISO Standard 19143 and in particular those of its currently available implementation in Degree [OSGeo 2016a]. For instance, even if the ISO Standard 19143 provides syntax for defining join-queries, the current version of Degree does not fully support them. Therefore, a conceptual query can contain only a resource type in the `from` clause.

Definition 5.1 (*Conceptual Query*). Given a GeoUML conceptual specification, a *conceptual query* is a query defined using the following BNF notation:

```
conceptual_query ::= select_clause from_clause [where_clause]
select_clause ::= SELECT select_expr {,select_expr}*
select_expr ::= identification_variable | single_valued_path_expr
single_valued_path_expr ::= state_field_path_expr |
                            single_valued_association_path_expr
from_clause ::= FROM feature_type_name identification_variable
where_clause ::= WHERE conditional_expr
conditional_expr ::= [NOT] conditional_term |
                     ( conditional_expr ) |
                       conditional_expr OR conditional_term |
                       conditional_expr AND conditional_term
conditional_term ::= comparison_predicate | spatial_predicate | temporal_predicate
```

where the `select_clause` and the `where_clause` will be described in more details in the following definitions, while the `from_clause` contains only the class name specification of the GeoUML feature type involved in the query. □

Definition 5.2 (*Identification variable*). An *identification variable* is a valid identifier declared in the `from` clause of a query. For instance, in the query `SELECT a FROM ST_ArchaeoPart a`, the identification variable `a` evaluates to any `ST_ArchaeoPart`. □

Definition 5.3 (*Path expression*). In GeoUML each feature type is characterized by a set of properties (*state-field*s) and a set of roles (*association-field*s) which can be reached from the identification variable using path expressions. A *path expression* is an identification variable followed by a navigation operator (.) and a state-field or an association-field. The type of the path expression is the type computed as the result of navigation; that is, the type of the state-field or association-field that is reached by the path expression. Depending on the navigability, a path expression that leads to an association-field may be further composed for obtaining the desired level of depth. In particular, the association-field can be substituted with another path expression that evaluates to a single-valued type (not a collection).

A `single_valued_path_expression` is a path expression which evaluates to a single-valued type, it can be a `state_field_path_expr`, if it terminates with a state-field, or a `single_valued_association_path_expr`, if it terminates with the name of an association-field in a one-to-one or many-to-one association. □

Definition 5.4 (*Conditional expression*). The conditional expression (`conditional_expr`) of a conceptual query is obtained by composing other conditional expressions with conditional terms (`conditional_term`) through logic operators (`AND`, `OR`, `NOT`). Each conditional term represents one of the WFS possible conditional predicates defined in the ISO Standard 19143. □

One of the characteristics of the GeoUML Language is the ability to define enumerations and hierarchical enumerations. The use of hierarchical enumerations is particularly useful in an interoperability context, because different agencies can share the same general concept and specialize it based on their needs. The archaeological domain is characterized by the use of many vocabularies in order to classify findings w.r.t. many aspects from the most objective one to the most interpretative one. Very often, these vocabularies can be shared in their general structure, but have to be specialized considering a particular domain of use.

For instance, as regards to the three considered contexts, movable and reused elements have not be catalogued in Rome, in order to give priority to topographical elements that denote the presence of a building structure. Conversely, they have been catalogued in the other two contexts, where the smaller size of the town and the smaller number of findings allowed to study even this kind of objects. Anyway, thanks to the use of a hierarchical structure for vocabularies, it has been possible to include into general terms, such as cult or public buildings, funerary context, and so on, even movable and reused findings, such as inscriptions, architectural elements, sculptural elements, and so on, without any impact on the work in Rome. Also queries that use values belonging to an enumeration in comparison conditions, can be made interoperable by exploiting their hierarchical structure, i.e. the usage of values belonging to a higher level of the hierarchy allows one to specify the same query on different systems even if the values used locally by each system are completely different.

Based on our experience, archaeological queries can be classified into three main categories: *literal queries*, which search objects based on a specific classification provided w.r.t. a given vocabulary, *spatial queries*, which search objects based on their position on the Earth surface using the address or the intersection with a particular area of interest, and *temporal queries*, which search objects w.r.t. a predefined historical period, or findings based on the belonging of one of its phases to a given period of time. Clearly, the three types can be combined obtaining the so called *mixed queries*.

In the following an example of these types of queries is provided, showing how they can be expressed w.r.t. the conceptual model presented in Section 4 and how they can be translated into interoperable WFS filters. Due to the lack of the join operator, in some cases it is necessary to perform more than one query to obtain the desired result, this is the case for instance of Example 5.6.

Example 5.5 (*Literal query*). Given the three instances of the *Star* model regarding the findings of Rome, Verona and Isola della Scala, search all archaeological partitions which regard a funerary context. The term funerary context presents a wide range of structures and monuments, that differ from each other not only for their building date, but also for their geophysical, ethnic and cultural context. Differently from Rome, Verona lacks completely of columbaria, as well as catacombs and rock tombs. Conversely, inscriptions, sarcophagi, architectural elements from funerary contexts (movable/reused elements) were recorded only in Verona and Isola della Scala, even though not in situ. The use of a hierarchical structure for the definition vocabulary of archaeological partitions allows to define a query able to retrieve all funerary contexts in the three realities even if their more specific terms are different. The query can be defined at conceptual level as follows:

```
SELECT a FROM ST_ArchaeoPart a
WHERE a.specific_definition.parent.name = "funeral context";
```

In particular, the property `specific_definition` of a generic archaeological partition `a`, has as domain a hierarchical enumeration. Each hierarchical value of the enumeration has a `name` property and an association with its `parent` which is in turn a value of the same enumeration. Therefore, the condition `a.specific_definition.parent.name` tests the name of the parent of the specific definition associated to `a`. This query will be translated into the following WFS filter:

```
<wfs:Query typeName="star:st_archaeo_part" aliases="AS">
  <fes:Filter><PropertyIsEqualTo>
    <ValueReference>objective_definition/parent/name</ValueReference>
    <Literal>funeral context</Literal>
  </PropertyIsEqualTo></Filter>
</wfs:Query>
```

Figure 13 illustrates the result of executing the query on the three datasets. Clearly, this is only an example of the expressive power provided by this kind of query. For instance, it is possible to traverse several associations, use different kind of definitions which can be more or less specific, compare the value of an attribute of a feature with the attribute of another feature instead of with a constant value.

Example 5.6 (*Spatial query*). Given the three instances of the *Star* model regarding the findings of Rome, Verona and Isola della Scala, search all archaeological partitions which are `ST_Structural_Element` and whose extent is at least 1 meter away from a particular finding. This query may be particularly useful during the interpretation process when archaeological partitions have to be grouped together in order to form archaeological units. In particular, given a meaningful finding which clearly identifies a particular monument, all its neighbouring structural elements are candidate to compose the same object. Performing this kind of query on all the three datasets, may allow one to determine the set of additional characteristics to be considered in order to isolate the elements that really compose an archaeological unit, from false positives.

This search can be defined at conceptual level using two queries: the first one will retrieve the structural element with the specified identifier, while the second one will retrieve the structural elements that are at a distance less than a 1 meter from it.

```
${geom} = ( SELECT a FROM ST_StructuralElement a WHERE a.id = 123 )
SELECT b FROM ST_StructuralElement b
WHERE distance( b.geometry, ${geom}) < 1;
```

Notice that the value produced by the first query has been stored into a variable `${geom}` which is used in the second query. This query will be translated into the two WFS filters below, the first one retrieves the structural elements with identifier "123" using an `IdOperator`:

```
<wfs:Query typeName="star:st_archaeo_part" aliases="AS SE">
  <fes:Filter><fes:ResourceId rid="123" /></fes:Filter>
</wfs:Query>
```

while the second one is a template that will be populated programmatically based on the result of the previous query, the `${geom}` denotes the dynamic parameter:

```
<wfs:Query typeName="star:st_archaeo_part">
  <fes:Filter><fes:DWithin>
    <fes:ValueReference>geometry</fes:ValueReference>
    ${geom}
    <fes:Distance uom="m">1</fes:Distance>
  </fes:DWithin></fes:Filter>
</wfs:Query>
```

Many other spatial operators can be used in the spatial query, in particular all the classical topological relations mentioned in Section 3.1. Moreover, a spatial attribute can be compared with a constant value or with the spatial attribute of another feature using the mechanism of the dynamic parameters.

Example 5.7 (*Temporal query*). Given the three instances of the *Star* model regarding the findings of Rome, Verona and Isola della Scala, search all archaeological partitions which are `ST_ManMadeObject` and whose building techniques are dated back to the Roman period. The query can be defined at conceptual level as follows:

```
SELECT b.archaeoPart FROM ST_BuildingTechnique b
WHERE b.period.start >= -509 AND b.period.end <= -476;
```

and can be translated into the WFS query below:

```
<wfs:Query typeName="star:st_building_technique">
  <ogc:PropertyName>archaeoPart</ogc:PropertyName>
  <fes:Filter><fes:And><fes:Or>
    <fes:After><fes:ValueReference>period.start</fes:ValueReference>
      <fes:Literal>-509</fes:Literal></fes:After>
    <fes:TEquals><fes:ValueReference>period.start</fes:ValueReference>
      <fes:Literal>-509</fes:Literal></fes:TEquals></fes:Or>
    <fes:Or><fes:Before><fes:ValueReference>period.end</fes:ValueReference>
      <fes:Literal>-476</fes:Literal></fes:Before>
    <fes:TEquals><fes:ValueReference>period.end</fes:ValueReference>
      <fes:Literal>-476</fes:Literal></fes:TEquals></fes:Or></fes:And>
  </fes:Filter>
</wfs:Query>
```

All the Allen's relations defined in Section 3.2 can be used in the temporal query. Moreover, it is possible to apply the same mechanism described for spatial query, in order to split a filter and combine the results using dynamic parameters.

The automatic translation of queries defined at conceptual level to WFS filters, is particularly useful in order to increase the usability of the WFS technology also by domain-expert users, which are not information scientists. Moreover, the set of most useful and typical queries can be configured into the system as so-called stored queries and invoked by simply calling their name together with a list of parameters. The following example illustrates the definition of a stored query in Degree which retrieves the set of archaeological partitions whose specific definition has a common parent in the hierarchical vocabulary.

Example 5.8 (*Stored query*). Given the three instances of the *Star* model regarding the findings of Rome, Verona and Isola della Scala, define a stored query which searches all archaeological partitions whose specific definition has a common parent in the hierarchical vocabulary given as parameter.

```
<StoredQueryDefinition id="urn:x-inspire:query:GetArchaeoPartForSpecDefinition"
  xmlns="http://www.opengis.net/wfs/2.0">
  <Title>GetArchaeoPartForSpecDefinition</Title>
  <Parameter name="specific_definition" type="xs:string" />
  <QueryExpressionText returnFeatureTypes="ST_ArchaeoPart"
      language="urn:ogc:def:queryLanguage:OGC-:WFSQueryExpression">
    <Query typeNames="ST_ArchaeoPart"><Filter><PropertyIsEqualTo>
      <ValueReference>specific_definition.parent.name</ValueReference>
      <Literal>${specific_definition}</Literal>
    </PropertyIsEqualTo></Filter></Query>
  </QueryExpressionText>
</StoredQueryDefinition>
```

Given such stored query, it can be invoked simply using the following HTTP request:

```
http://localhost:8080/services?
  request=GetFeature&
  storedquery_id=urn:x-inspire:storedQuery:GetArchaeoPartForSpecDefinition&
  specific_definition=Funerary%20context
```

Many improvements can be developed in the translation of conceptual queries to WFS filters. In particular, the lack of join operations in currently available tools, such as Degree, undoubtedly reduces the level of automation, since in many cases it is necessary to programmatically combine multiple filters in order to obtain the desired result. However, the performed experiments highlight the potentiality and the benefits of providing the user with the ability of specifying conceptual queries.

5.4. An Architecture Overview of the Proposed Archaeological SDI

In order to illustrate how the different solutions described in the previous sections can work together in an Archaeological SDI, Figure 14 shows the various modules of such SDI and describes how they interact with the others. The main modules are:

- the *GeoUML Catalogue* that manages the shared conceptual specification and automatically generates: (i) the physical mappings (PMs) specifying the structure of the local databases, (ii) the XSD file containing the description of all the classes with their attributes and of all the association roles between them in a way compliant with the ISO Standard 19136 Annex E, together with the XML configuration file for Degree (XML mapping file + WFS); (iii) an XML representation of the conceptual model and of each physical mapping generated for configuring the WFSs (SCS files);
- the *local spatial database management systems* containing the datasets of a specific provider of the SDI;

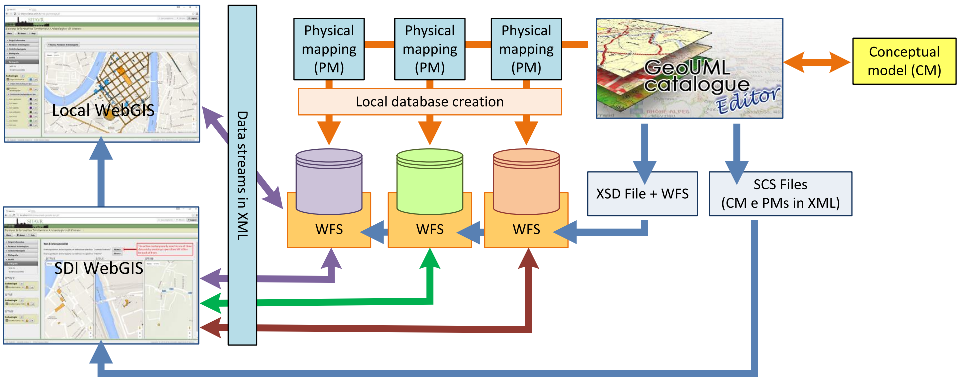


Fig. 14. Architecture of the proposed Archaeological SDI.

- the *local application servers* providing access to the local data by means of a WFS that adopts the shared XML syntax and extracts data from the local database following the defined mapping files;
- the (local and SDI) *WebGIS applications* that are able to interact with any WFS of the SDI and accessing the data by means of conceptual queries specified by the user.

Notice that the proposed approach for building the Archaeological SDI can benefit from the GeoUML tools in several ways: (i) in the generation of the local databases; (ii) in the configuration of the WFS on the local application servers; (iii) in the implementation of the local or shared web-based interfaces for accessing and querying the archaeological information produced by the providers that cooperate in the SDI.

6. CONCLUSION

The paper lays the basis for the development of an archaeological SDI through which domain experts can share data, tools and competencies in an effective way. This interoperability can be particularly useful in the archaeological domain, since the data discovered by other agencies can be used during the dating or interpretation process performed in other regions with overlapping spatio-temporal or thematic characteristics. With this purpose in mind, the contribution of the paper is twofold: firstly, it proposes a spatio-temporal conceptual model for archaeological data, called *Star* model, which is compliant with the ISO Standards of the 19100 family. Secondly, it applies and enhances the GeoUML methodology and tools in order to support and promote the development of interoperable applications and services.

The *Star* model has been developed starting from the experience performed during a collaboration among the Archaeological Special Superintendence of Rome, the Superintendence for Archaeological Heritage of Veneto region and the University of Verona. The work was started in 2011 and has required a great effort in order to define a common data model able to meet the needs of different realities: from metropolis to rural areas. Many of the difficulties have regarded not only the definition and formalization of the set of core concepts, but also the agreement on common thesauri and terms used for the description of archaeological objects. The model is now suitable for consistently representing archival documents (reports, plans, drawings, photographs and other materials), excavations processes and other archaeological researches (field surveys, geophysical prospections, etc.), archaeological findings and remains, spatial and temporal features. A future version of the model will include a set of primitives for the description of stratigraphic analysis. Moreover, as regards to the mentioned thesauri, a work is started in order to internationalize them and define correspondence with the

Getty Art & Architecture Thesaurus. At the same time, the definition of a translation towards the CIDOC CRM is started with reference also to the CRM$_{archeo}$ extension.

The GeoUML methodology and tools have been applied in order to formally define the conceptual model and some extensions and improvements have been developed to increase the degree of automation and support the development of an archaeological SDI. As regards to this aspect the main contributions are: (a) the automatic configuration of a WFS for displaying and managing archaeological data, (b) the development of a new WebGIS which is able to visualize data provided through a WFS and to exploit XLinks in order to traverse associations among objects, and (c) the development of a tool for automatically translate a query defined at conceptual level into a WFS filter. As future work, the GeoUML language will be enhanced to natively supports all temporal types defined by the ISO Standard 19107, while the GeoUML Catalogue and Validator will be extended for respectively specifying and checking the conformance of temporal constraints, besides to spatial ones. Finally, as the available tools will support join conditions in WFS filter, the query translation tool will be accordingly enriched.

Starting from 2011 many researchers have been involved in the three presented case studies for collecting data using the *Star* model. In particular, while the case of the rural town (Isola della Scala), has involved few people and only some months of work, the case of Rome has involved a rich group of archaeologists that constantly collect data coming from different sources and redefine them using the proposed model. At now the database of Rome contains approximately 4,000 information sources, 13,000 archaeological partitions, while the interpretation process involving the definition of archaeological units is just beginning. Conversely, the collection of data in Verona is started in the last year and at now its database contains approximately 200 information sources, 400 archaeological partitions and few archaeological units.

The first experiments in developing an archaeological SDI which involved some Italian contexts, including the capital city Rome, highlight the benefits of a sharing and deep collaboration between agencies in performing the archaeological process. The constant discussion between archaeologists coming from different contexts led to the definition of data with better quality and inj many cases shortened the time required to perform the interpretation process. For example, it is now possible to compare building (or road construction) techniques in town and in the countryside and extract some relevant statistical figures.

To ensure the long term viability of the built SDI, a constant collaboration is required between the different agencies. In particular, it is necessary to guarantee that they continue to adhere to the common model, preventing that their particular needs can overcome the interoperability purposes. A great incentive in this direction is not only the ability for domain experts to perform interoperable queries on all the systems, but also for a public audience that can enjoy from such integrated consultation, and for other agencies coming from different contexts (such as public infrastructure agencies) that have the need to acquire archaeological data in their everyday's work.

REFERENCES

J. F. Allen. 1983. Maintaining Knowledge About Temporal Intervals. *Communications of the ACM* 26, 11 (1983), 832–843.

F. Anichini, F. Fabiani, G. Gattiglia, and M. L. Gualandii (Eds.). 2011. *MAPPA Project. Methodologies Applied to Archaeological Potential Predictivity*. Vol. I. Edizioni Nuova Cultura.

J. A. Barceló. 2010. Computational Intelligence in Archaeology. State of the Art. In *Computer Applications & Qualitative Methods in Archaeology (CAA), Proceedings of the 37th International Conference*. 11–21.

P. Basso, A. Belussi, P. Grossi, and S. Migliorini. 2013. Towards the Creation of an Archaeological Urban Information System: Data Modeling of the Historical Heritage of Verona. In *Proc. of AGILE 2013, Workshop on Integrating 4D, GIS and Cultural Heritage*. 1–3.

A. Belussi, P. Cipriano, S. Migliorini, M. Negri, and G. Pelagatti. 2014. Design of the Data Transformation Architecture for the INSPIRE Data Model Browser. In *AGILE'2014 International Conference on Geographic Information Science*. 1–2.

A. Belussi and S. Migliorini. 2014. A Framework for Managing Temporal Dimensions in Archaeological Data. In *Temporal Representation and Reasoning (TIME), 2014 21st International Symposium on*. 81–90.

A. Belussi and S. Migliorini. 2017. A spatio-temporal framework for managing archeological data. *Annals of Mathematics and Artificial Intelligence* (2017), 1–44. DOI:http://dx.doi.org/10.1007/s10472-017-9535-0

A. Belussi, S. Migliorini, and P. Grossi. 2015. Managing Time Dimension in the Archaeological Urban Information System of the Historical Heritage of Rome and Verona. In *The 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*. Archaeopress, 235–244.

A. Belussi, M. Negri, and G. Pelagatti. 2006. An ISO TC 211 Conformant Approach to Model Spatial Integrity Constraints in the Conceptual Design of Geographical Databases. In *Advances in Conceptual Modeling - Theory and Practice: ER 2006 (CoMoGIS Workshops)*. Springer Berlin Heidelberg, Berlin, Heidelberg, 100–109. DOI:http://dx.doi.org/10.1007/11908883_13

B. Bruno, P. Basso, P. Grossi, A. Belussi, and S. Migliorini. 2015. SITAVR Project - An Archaeological Charter for Verona. *Archeologia e Calcolatori* Suppl. 7 (2015), 157–167.

CISIS. 2016. Centro Interregionale per i Sistemi informatici, geografici e statistici. (2016). http://www.cisis.it/ Last accessed Nov. 2016.

E. Clementini and P. Di Felice. 1995. A Comparison of Methods for Representing Topological Relationships. *Inf. Sci. Appl.* 3, 3 (1995), 149–178.

E. Clementini and P. Di Felice. 1996. A Model for Representing Topological Relationships Between Complex Geometric Features in Spatial Databases. *Inf. Sci.* 90, 1-4 (1996), 121–136.

E. Clementini, P. Di Felice, and P. van Oosterom. 1993. A Small Set of Formal Topological Relationships Suitable for End-User Interaction. In *Proceedings of the Third International Symposium on Advances in Spatial Databases (SSD '93)*. Springer-Verlag, London, UK, UK, 277–295.

B. De Roo, P. De Maeyer, and J. Bourgeois. 2016. Information Flows as Bases for Archeology-Specific Geodata Infrastructures: An Exploratory Study in Flanders. *Journal of the Association for Information Science and Technology* 67 (2016), 1928–1942. Issue 8.

B. De Roo, K. Ooms, J. Bourgeois, and P. Maeyer. 2014a. Bridging Archaeology and GIS: Influencing Factors for a 4D Archaeological GIS. In *Proceedings of the 5th Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*. Springer International Publishing, 186–195.

B. De Roo, N. Van de Weghe, J. Bourgeois, and P. De Maeyer. 2014b. The Temporal Dimension in a 4D Archaeological Data Model: Applicability of the GeoInformation Standard. In *Innovations in 3D Geo-Information Sciences*. Springer International Publishing, 33–55.

C. De Runz and E. Desjardin. 2010. *Imperfect Spatiotemporal Information Analysis in a GIS: Application to Archæological Information Completion Hypothesis*. Springer Berlin Heidelberg, Berlin, Heidelberg, 341–356. DOI:http://dx.doi.org/10.1007/978-3-642-14755-5_13

M. J. Egenhofer and R. Franzosa. 1991. Point-set topological spatial relations. *International Journal of Geographic Information Systems* 2, 5 (1991), 161–174.

European Commission 2007. *INSPIRE Directive*. European Commission. http://inspire.jrc.ec.europa.eu Last accessed Nov. 2016.

European Commission. 2016. ARIADNE Advanced Research Infrastructure for Archaeological Dataset Networking in Europe. (2016). http://www.ariadne-infrastructure.eu Last accessed Nov. 2016.

A. Felicetti, A. Masur, A. Kritsotaki, G. Hiebel, K. May, M. Theodoridou, M. Doerrand, P. Ronzino, S. Hermon, and W. Schmidle. 2016. Definition of the CRM$_{archaeo}$. An Extension of CIDOC CRM to support archaeological excavation process. (2016). http://www.cidoc-crm.org/crmarchaeo/ModelVersion/version-1.4.1 Last accessed Nov. 2016.

M. Frassine and G. Naponiello. 2012. RAPTOR: archeologia e tutela. Verso la Pubblica Amministrazione digitale. *Archeologia e Calcolatori* 23 (2012), 81–99.

Getty Conservation Institute and World Monuments Fund. 2016. Arches – An open source data management platform for the heritage field. (2016). http://archesproject.org/ Last accessed Nov. 2016.

Google 2016. *Google Maps APIs*. Google. https://developers.google.com/maps/ Last accessed Nov. 2016.

Edward C. Harris. 1989. *Principles of archaeological stratigraphy, 2nd ed.* Academic Press.

ICOM/CIDOC CRM Special Interest Group. 2016. Definition of the CIDOC Conceptual Reference Model, version 6.2.2. (2016). http://www.cidoc-crm.org/.

ISO 2002. *ISO 19108 Geographic Information – Temporal Schema*. ISO. https://www.iso.org/standard/26013.html Last accessed Nov. 2016.

ISO 2003. *ISO 19107 Geographic Information – Spatial Schema*. ISO. https://www.iso.org/standard/26012.html Last accessed Nov. 2016.

ISO 2010a. *ISO 19142 Geographic Information – Web Feature Service*. ISO. https://www.iso.org/standard/42136.html Last accessed Nov. 2016.

ISO 2010b. *ISO 19143 Geographic Information – Filter Encoding*. ISO. https://www.iso.org/standard/42137.html Last accessed Nov. 2016.

M. Katsianis, S. Tsipidis, K. Kotsakis, and A. Kousoulakou. 2008. A 3D Digital Workflow for Archaeological Intra-Site Research using GIS. *Journal of Archaeological Science* 35, 3 (2008), 655–667.

Leiden University. 2016. Archol – Archaeological Unit. (2016). http://www.archol.nl/ Last accessed Nov. 2016.

P. McKeague, A. Corns, and R. Shaw. 2012. Developing a Spatial Data Infrastructure for Archaeological and Built Heritage. *International Journal of Spatial Data Infrastructure Research* 7 (2012), 38–65.

Oracle 2013. *JSR 338: Java Persistence API, Version 2.1*. Oracle. http://download.oracle.com/otn-pub/jcp/persistence-2_1-fr-eval-spec/JavaPersistence.pdf Last accessed Nov. 2016.

Oracle 2015. *JSR 372: JavaServer Faces (JSF 2.3) Specification*. Oracle. http://download.oracle.com/otn-pub/jcp/jsf-2_3-edr-spec/JSF_2_3_EDR.pdf Last accessed Nov. 2016.

OSGeo. 2015. *GeoServer User Manual, Version 2.9*. Open Source Geospatial Foundation. http://docs.geoserver.org/latest/en/user/ Last accessed Nov. 2016.

OSGeo. 2016a. *Deegree Webservices Documentation, Version 3.3.18*. Open Source Geospatial Foundation. http://repo.deegree.org/content/repositories/public/org/deegree/deegree-webservices-handbook/3.3.18/deegree-webservices-handbook-3.3.18.zip Last accessed Nov. 2016.

OSGeo. 2016b. *OpenLayers 3*. Open Source Geospatial Foundation. http://openlayers.org/en/v3.14.2/doc/tutorials/ Last accessed Nov. 2016.

OSGeo. 2016c. *QGIS User Guide, Version 2.8*. Open Source Geospatial Foundation. http://docs.qgis.org/2.8/en/docs/user_manual/ Last accessed Nov. 2016.

G. Pelagatti, M. Negri, A. Belussi, and S. Migliorini. 2009. From the Conceptual Design of Spatial Constraints to their Implementation in Real Systems. In *Proceedings of the 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (GIS '09)*. ACM, New York, NY, USA, 448–451. DOI:http://dx.doi.org/10.1145/1653771.1653841

J. D. Richards. 2008. *Managing digital preservation and access: The Archaeology Data Service*. Left Coast Press, 173–94.

J. D. Richards, K. Niven, and S. Jeffrey. 2013. *Preserving Our Digital Heritage: Information Systems for Data Management and Preservation*. Springer London, London, 311–326. DOI:http://dx.doi.org/10.1007/978-1-4471-5535-5_16

S. Ross, B. Ballsun-Stanton, A. Sobotkova, and P. Crook. 2015. *Building the Bazaar: Enhancing Archaeological Field Recording Through an Open Source Approach*. De Gruyter Open, 111–129.

E. Scampoli, A. Sahlin, and G. Andreozzi. 2013. ARCHEOFI (archeologia.comune.fi.it) un sistema informativo per la gestione e la condivisione dei principali dati archeologici di Firenze. In *Archeologia a Firenze: Città e Territorio: Atti del Workshop*. 405–424.

M. Serlorenzi (Ed.). 2010. *SITAR – Sitema Informativo Territoriale Archeologico di Roma, Atti del I Convegno*. Iuno.

D. R. Snow, M. Gahegan, C. L. Giles, K. G. Hirth, G. R. Milner, P. Mitra, and J. Z. Wang. 2006. Cybertools and Archaeology. *Science* 311 (2006), 958–959. Issue 5763. DOI:http://dx.doi.org/doi:10.1126/science.1121556

M. Van Ruymbeke, C. Carr, V. Delfosse, M. Pfeiffer, and R. Billen. 2015. Towards an Archaeological Information System: Improving the Core Data Model. In *The 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology*. Archaeopress, 245–253.

Vivid Solutions 2003. *JTS Topology Suite Technical Specifications, Version 1.4*. Vivid Solutions. http://www.vividsolutions.com/jts/bin/JTS\%20Technical\%20Specs.pdf Last accessed Nov. 2016.

D. Wheatley and M. Gillings. 2002. *Spatial technology and archaeology: the archaeological applications of GIS*. Taylor & Francis.

A. Zoghlami, C. de Runz, H.n Akdag, and D. Pargny. 2012. *Through a Fuzzy Spatiotemporal Information System for Handling Excavation Data*. Springer Berlin Heidelberg, Berlin, Heidelberg, 179–196. DOI:http://dx.doi.org/10.1007/978-3-642-29063-3_10

Received XXXX; revised XXXX; accepted XXXX

Online Appendix to:
An Interoperable Spatio-Temporal Model for Archaeological Data Based on ISO Standard 19100

SARA MIGLIORINI, University of Verona (Italy)
PIERGIOVANNA GROSSI, University of Verona (Italy)
ALBERTO BELUSSI, University of Verona (Italy)

DOI:http://dx.doi.org/10.1145/0000000.0000000

Example .1 (*St_NamedYearRange*). Example of `ST_NamedYearRange` of the *Star* which is an example of ordinal reference system.

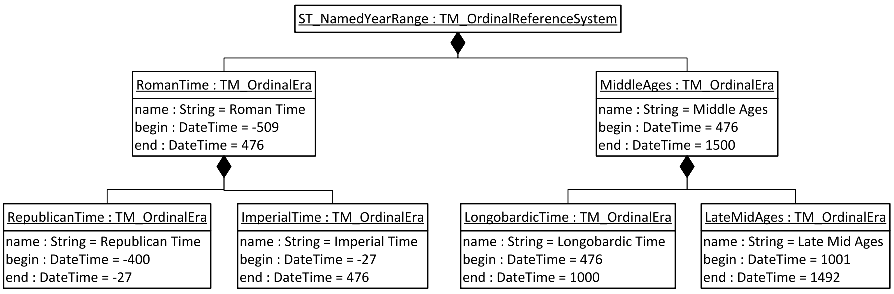


Fig. 15. Examples of ordinal eras used in the *Star* model.

Example .2. Let us consider four archaeological finds labeled as f_1, f_2, f_3 and f_4 which are coarsely dated as follows: f_1, f_2 are located in the 19th century, while f_3 is dated 1850 and f_4 is dated 1820. Besides these geometrical values, the following temporal relations have been detected: f_1 before f_2 and f_3, while f_2 before f_3 and after f_4. This knowledge can be represented by the topological complex in Figure 16. Dates associated to nodes f_3 and f_4 are realized as the years 1850 and 1820, respectively. Conversely, dates related to nodes f_1 and f_2 are not realized, but they are located between two dummy nodes representing the years 1800 and 1899. Given such topological structure some automatic reasoning techniques can be applied in order to realize such dates. In particular, all dates between 1820 and 1850 could be consistent realizations for f_2, while all dates between 1800 and 1820 could be consistent realizations for f_1. This does not exclude that dates between 1820 and 1850 could also be consistent realization for f_1, provided that we can have a more precise information about f_2. For example, if some additional information becomes available about the dating of f_2 which restricts its possible date interval to 1840 and 1850, a consistent realization for f_1 can be located between 1800 and 1840.

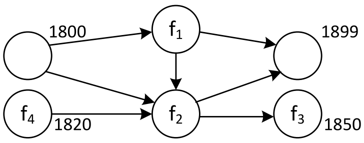


Fig. 16. Example of topological complex representing ordinal temporal relations between chronologies of archaeological partition.