RCC8 for CIDOC CRM: Semantic Modeling of Mereological and Topological Spatial Relations in Notre-Dame de Paris

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Abstract

This work aims at the conceptual and ontological modeling of the abstract spatial relations in heterogeneous cultural heritage data. This work focuses on built heritage, studying the case of Notre-Dame de Paris. The spatial information is a transversal component across the metadata and paradata collection in the datasets about Notre-Dame. The integration using spatial information is crucial for archival, query, analysis, and visualization. Cultural heritage data integration implies the use of the CIDOC CRM ontology, whereas the real-life data challenge the core model because of the complexity of spatial relations. This contribution aims at the analysis of this complexity in terms of mereological and topological spatial relations. It opens an opportunity to explore the conceptualization of space and the abstract spatial relations that go beyond the geometric or the geographic aspects. The contribution presents the conceptual and ontological modeling about the abstract spatial relations using both CIDOC CRM, its extension CRMgeo, geoSPARQL, and RCC8.

Keywords

Cultural Heritage (CH), Built Heritage, Semantics, spatial, CIDOC CRM, Notre-Dame de Paris, GeoSPARQL, CRMgeo, RCC8, knowledge graph, ontology modeling, interoperability, IFC, spatial annotation, space, place, topology, mereology, mereo(topo)logy, ontology, knowledge representation, spatial relations, spatial cognition

1. Introduction

This contribution is based on the case study of Notre-Dame de Paris as an example of big data in the cultural heritage (CH) field. The characteristics of big data for CH are: real-life data, messy, highly heterogeneous, and specialized in unstructured or semi-structured datasets. The object of study in cultural heritage is typically tied with both the materiality of objects (buildings, artifacts) and their non-materiality. The case study of Notre-Dame is no exception: on one hand, it illustrates the utmost importance of the cathedral as built work, built components, as well as archaeological artifacts. After the fire, the operations of cleaning, extracting, and sorting

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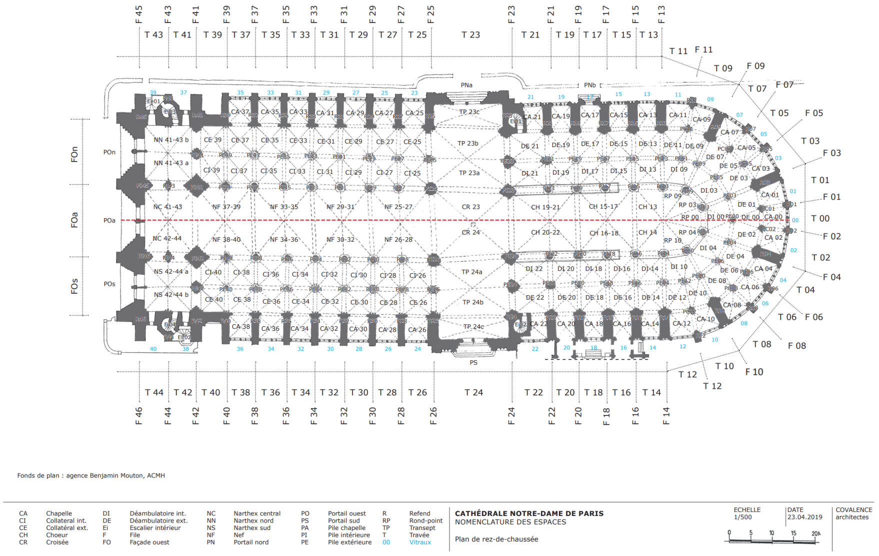

Figure 1: Plan of the ground floor of the cathedral with the nomenclature entities as defined by the architects of the restoration project (@RNDP).

remains and archaeological workflow of inventory, study, and analysis enlighten the porosity between archaeological methods (excavation documentation, inventory, and documentation), with operational activities. On the other hand, all the activities for the restoration or the research on Notre-Dame have in common the characteristic of being spatialized data [1, 2, 3, 4]. Thus, the information about location, space, and place can be understood as shared anchors across highly heterogeneous datasets and information. The most intuitive and foundational definition of architecture is the built thing, that is the architecture qua building or built work. Human beings continuously interact with the built materiality through the non-materiality of space. Space as emptiness is formed and defined by the materiality that affects its existence. That relation between fullness and emptiness is what makes possible architecture as lived and experienced space. The cathedral itself, as architecture, is by essence a spatially complex object [Figure 1]. We will build upon this definition in the rest of this article as scope of modeling about space.

In the perspective of implementing a knowledge graph using CIDOC CRM as integration ontology for Notre-Dame's data, the integration using spatial information is crucial. Information about space and place presents itself as an entry point for the indexing and structuration of datasets, their enrichment, query, analysis, and visualization [5, 6]. It promotes consistency within the knowledge base due to the transversality of the spatial question in the documentation of the spaces of Notre-Dame, the places, the built works and built elements. This contribution does not focus on the implementation process per se, but rather on the conceptual problems that emerge from the different models and their inherent conceptualizations of space.

The Notre-Dame dataset analysis shows the need for a foundational set of relations that consistently express spatial relationships in terms of topology and mereology. This question

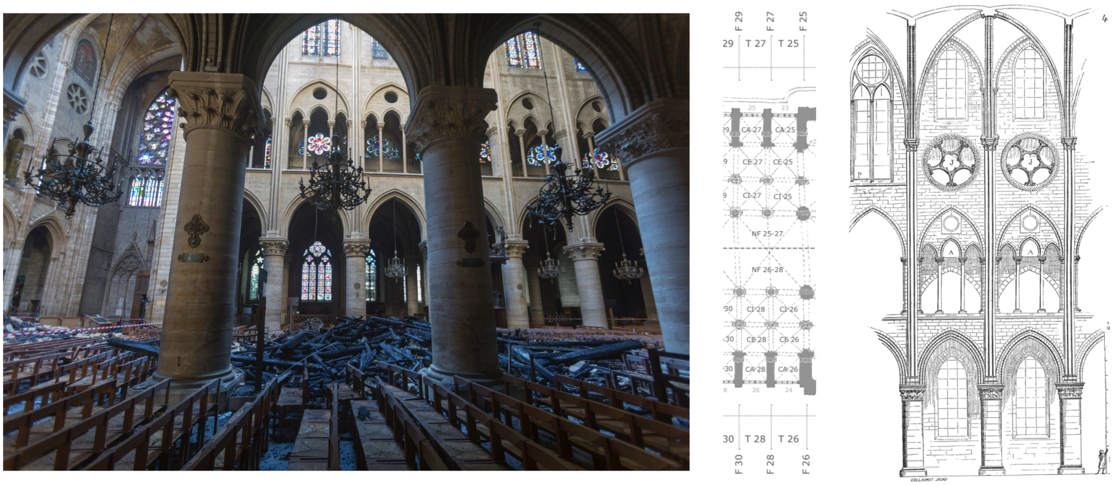

Figure 2: (a) A photograph taken from the collateral (@Komenda/C2RMF), (b) extract of the nomenclature (@RNDP), (c) section on the interior (@E. Viollet-le-Duc).

goes beyond the location information. The question of space cannot be limited either to its geographic concept, geometric and GIS information. Plenty of spatial and geometric data is available but there is a lack of semantics about space and place. Hence, the challenge of the complexity of spatial relations and data is a multiple level problem that this paper aims to unfold step by step. To recap, we are looking at how to semantically express the complexity of the spatial relations in order to have an accurate description of the mereological and topological spatial relations between built components, spaces, and places in Notre-Dame case study [Figure 2].

Then this work builds upon this real-life data: it aims at the knowledge representation of the complex spatial relations in heterogeneous cultural built heritage data systematically expressed. The contribution presents the conceptual modeling of these topological relations using both the CIDOC CRM (with its extension CRMgeo) and the RCC8. From the scope of the CIDOC CRM, this modeling is constructed as the interface between RCC8 and CRM to allow the expression of the needed abstract topological relations. This work is thought in analogy with existing modeling: firstly, in the CIDOC CRM model, the entity crm:E55_Type acts as a bridge to SKOS where the thesauri are externally managed. Similarly, the objective is here to investigate the compatibility between CIDOC CRM and RCC8 models. Secondly, the modeling of time properties is explicitly inspired from Allen principles: we propose to apply a similar perspective for the question of spatial relations. In brief, we posit that the RCC8 can play the role of a semantic module for the topological relationships, in combination with the CIDOC CRM as domain ontology for the integration of heterogeneous CH data.

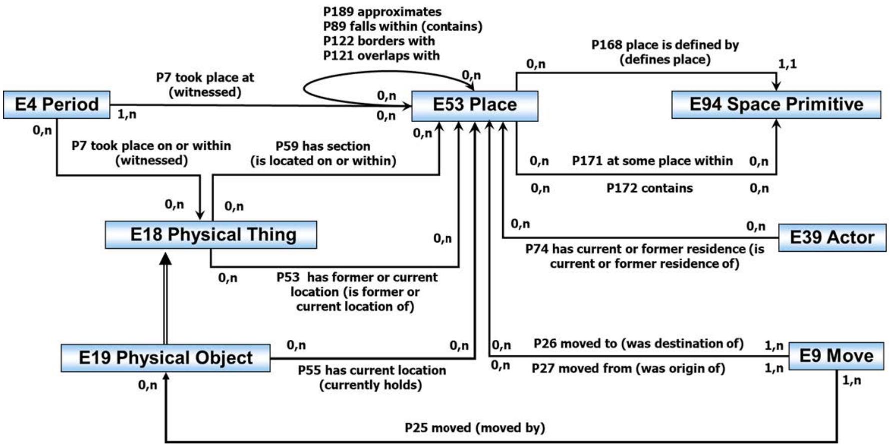

Figure 3: Basic CIDOC CRM Properties and classes about spatial relations in CIDOC CRM 7.1.2 [11].

2. State of the Art

The conceptualization and formalization of space and spatial relations are identified as the speciality of geomatics and geography. The geoinformation community is built around the data technical workflows and implementation of geodata. The manipulation and interoperability of geodata is made possible with the standardization effort by the OGC Standards Schemas. Organized as a technical stack, this multi-layered and multi-faceted implementations encompasses conceptual modelings (ie. Geography Markup Language (GML) [7], Keyhole Markup Language (KML) [8]), geometry encodings (ie. Well-Known Text, GeoJSON), services, and standard APIs. The focus on geoinformation does not fit our scope completely because space is conceptualized as a geographic concept based mostly on 2D representations, geometry and GIS technology [9].

The OGC geoSPARQL model serves as an interface to the semantic web for the geoinformation. The limits in scope of OGC Standard are acknowledged by geoSPARQL as follows: “GeoSPARQL does not define a comprehensive vocabulary for representing spatial information. Instead GeoSPARQL defines a core set of classes, properties and datatypes that can be used to construct query patterns. Many useful extensions to this vocabulary are possible, and we intend for the Semantic Web and Geospatial communities to develop additional vocabularies for describing spatial information” [10]. GeoSPARQL is designed as an open model, allowing communities to specify the model to their usage through the addition of vocabularies. In addition, this design allows an hybridization of the model, whether by the making of an extension or ontology merging. Nevertheless, the geoSPARQL model is still implicitly bound by the technical implementation of the 2D space information. Subsequently it bears the same geometric and geographic representation of the concepts of space.

In the scope of cultural heritage data integration, the CIDOC CRM is a go-to model as a starting point [12]. It is characterized by the central role of the temporal entities and its event-oriented modeling. The materiality of architectural objects or built works falls under the scope of E18 Physical thing and subclasses, while spaces are rather characterized as instances of E53 Place. The spatial relations are synthetically described in the introduction of the model [Figure 3]. The

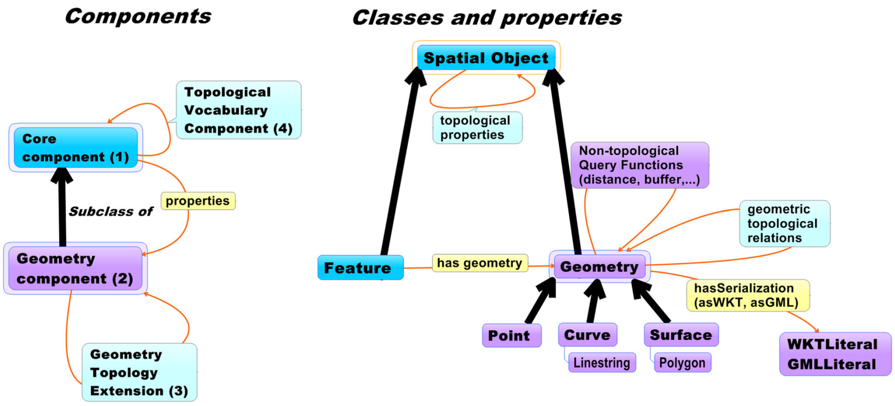

Figure 4: Overview of CRMgeo and GeoSPARQL [13].

base model is expanded by different extensions that take into account aspects of spatial modeling. CRMgeo [13, 14] is to bridge geoSPARQL to CIDOC CRM. It discriminates between phenomenal and declarative places classes that help define the relation between space and geometries. To express spatial relations in CRM, CRMgeo depends on both the CRM spatial relations and the geoSPARQL interface. Still in the CRM family of models, CRMba [15] -b.a. stands for building archaeology- considers the building as a stratigraphic object from the perspective of an archaeologist. In stratigraphic analysis, spaces are layered as stratigraphic units. The formalization of the stratigraphic units of a built works are sketched through mereological relations and an undefined topological relation.

In the Architecture, Engineering and construction (AEC) industry, the standard Industry Foundation Classes (IFC) defined for Building Information Modelling (BIM) have as powerful a bias as stratigraphic analysis. The partitioning of spaces is also done from an operational point of view: the site, building, storey, spaces and elements are differentiated in a mereological fashion [16]. In the context of semantic web, this model is accessed via ifcOWL [17] or replicated in the Building Ontology Topology (BOT) [18]. We can observe here a modelization pattern similar to the way in which a technical object, such as a STEP model, is partitioned. The main difference is that parts of technical objects are interrelated by (mechanical/physical) relations, defining the interaction, while IFC parts do not refine the interface.

Since the CIDOC CRM is a domain ontology that has been developed bottom-up, the modeling reflects what is the most commonly documented in specific CH fields. We showed the need for a more generic representation of space or spatial relations. In this direction, the work of [19, 20] investigates a modeling of foundational relations (FORT) in relation to the most known foundational ontologies (BFO, DOLCE, UFO). They point out the foundational relational aspect that is key in spatial relations: Entity-Location, Location, Connection, Parthood, Dependence, Constitution, Membership, Unity. We identified the need for a similar level of genericity in relations as in [19, 20] but with the specificity of application domain in cultural heritage, that is the scope of the CIDOC CRM ontology.

IFC, CRMgeo, CRMba, GIS related models are known models, that means they are operational and used by specific communities. They carry their own bias in the definition of space and

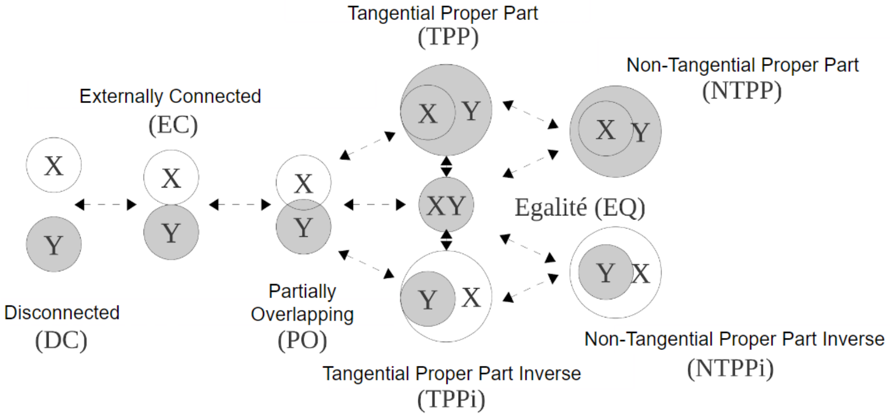

Figure 5: Schema representing the RCC8 [26] modified (translated).

put their focus on spatial relations as geometry management. The mereological aspect is systematically taken into account as a hierarchy that can be represented as a tree-like structure. The topological relations are developed according to operational needs and context, they are more prone to the modelisation bias. An abstract way to represent them is a graph-like structure. In built works, entities considered by these relations are heterogeneous (space, built work, elements...), defined by both a geometry or abstract from it. In the next part, we will then look at the method to express mereological and topological relations between heterogeneous elements composing space. It will build on the alignment of RCC8 relations with the CRM model for phenomenal places.

3. Methodology

The objective of this contribution is to model spatial semantics where space is not just understood as geographic or geometric information as in [21].

We can reason about the relative positions of the entities that make the accounted spaces up. There are three main categories of spatial relations [22]: metric relations, topological relations and order relations. In this work, we are interested in topological relations. Topology can be defined as the set of perceived relations that enable us to situate objects in relation to one another. To be more specific, topology is the study of properties of spaces that are invariant under any continuous deformation. Thus, topological relationships are the subject of an abundant scientific literature using a wide range of sound mathematical models [23]. The dominant models are: the 9-IM model (9-Intersection Model), Egenhofer, and the RCC model (Region Connection Calculus). Basically, these models distinguish several fundamental topological relationships identified by the Region Connection Calculus (RCC) between spatial entities [24, 25]. The main difference between them lies in the dimension of the handled entities. The characterisation of spaces in buildings consists in identifying 3D regions, whether empty or filled, often presented in orthogonal projections.

Table 1
The eight spatial relations in RCC8 with labels and definitions.

Symbol	Name	Note
DC	Disconnected	The two regions are completlydisconnected (there are no common pieces)
EC	Externally Connected	The boundaries of the regions touch, but their interiors are disjoint
PO	Partially Overlapping	The two regions partially overlap (there are disjoint sub parts, and some part of one is included in some part of the other)
EQ	EQual	Two regions have the same spatial extent
TPP	Tangential Proper Part	The first region is entirely inside the second region and their boundaries touch each other from the inside
TPPi	Tangential Proper Part Inverse	The first region contains the second region and their boundaries touch each other from the inside
NTPP	Non-Tangential Proper Part	The first region is entirely inside the second region and their boundaries do not touche
NTPPi	Non-Tangential Proper Part Inverse	The first region contains the second region and their boundaries do not touch

The RCC8 formalism defines eight elementary relationships [Figure 5] to describe spatial relations between entities whose primitives are regions [Table 1]. [27] state that RCC8 formalism is dimension independent, applicable in $\mathbb{R}^n$, and then demonstrate each of the axioms and subsequent theorems: “The language RCC8 is a widely-studied formalism for describing topological arrangements of spatial regions. The variables of this language range over the collection of non-empty, regular closed sets of n-dimensional Euclidean space, here denoted ($RC + \mathbb{R}^n$), and its non-logical primitives allow us to specify how the interiors, exteriors and boundaries of these sets intersect” [27, 28]. However, the RCC system does not distinguish between open and closed geometries. Conceptually, human thought is capable of manipulating abstract notions of openness, such as the interior of a room, a building, etc. [29]. Moreover, Dia Miron points out that inference procedures based on this formalization are not the most efficient, and reasoning can sometimes turn out to be incomplete or undecidable [30][26].

As explained by [31], “Besides CIDOC CRM spatial classes (E53 Place, E44 Dimension, E47 Spatial coordinates and E94 Space Primitives), the model offers properties which fulfill most common topological spatial relations (Dimensionally Extended nine-Intersection Model (DE-9IM), Region Connection Calculus (RCC8))[...]. Finally, CIDOC CRM defines class E92 Space Time Volume that designates four dimensional point sets and has temporal (CIDOC:P160) and spatial (CIDOC:P161) projections. Besides this, the CRMgeo extension provides spatial and temporal classes and properties dedicated to formulate declarative information. It also provides links with GeoSPARQL. Indeed, these links with the OGC GeoSPARQL standard are necessary to make use of the conceptualization and formal definitions that have been developed in the Geoinformation community” [31]. Building upon the same observation, our approach bears some major differences: this contribution looks only at spatial relations (instead of spatio-temporal) for a rather diverse community of architects, archaeologists, conservators, etc.

Table 2
Analysis of the CIDOC CRM properties against the RCC8 relations: we check whether the CIDOC CRM properties express some topological relationships. We specify if the topology is rather defined in (a) the scope note, (b) the examples or if it is (c) unspecified.

Domain	Property label	Range	DC	EC	PO	EQ	TPP	TPPi	nTPP	nTPPi
E18	P53 has current or former location	E53				x(a)	x(b)		x(b)	
E18	P59 has section	E53						x		x
E18	P156 occupies	E53				x(a)				
E18	P157i provides reference space for	E53	x	x	x	x	x	x	x	x
E19	P55 has current location	E53				x(a)	x(b)		x(b)	
E53	P53i is former or current location of	E18				x(a)		x(b)		x(b)
E53	P55i currently holds	E19				x(a)		x(b)		x(b)
E53	P59i is located on or within	E18					x		x	
E53	P89 falls within	E53					x		x	
E53	P89i contains	E53						x		x
E53	P121 overlaps with	E53			x	x(c)	x(c)	x(c)	x(c)	x(c)
E53	P122 borders with	E53		x			x	x		
E53	P156i is occupied by	E18				x		x		x
E53	P157 is at rest relative to	E18	x	x	x	x	x	x	x	x
E53	P168 place is defined by	E94				x		x(a)		x(a)
E53	P171 at some place within	E94				x	x		x	
E53	P172 contains	E94				x		x		x
E53	P189 approximates	E53	x	x	x	x	x	x	x	x
E92	P10 falls within	E92				x	x		x	
E92	P10i contains	E92				x		x		x
E92	P132 spatiotemporally overlaps with	E92			x	x(c)	x(c)	x(c)	x(c)	x(c)
E92	P133 spatiotemporally separated from	E92	x							
E94	P168i defines place	E53				x	x(a)		x	

and not for the geoinformation community specifically. As shown in the state of the art, the conceptualization of space and spatial objects differs in terms of scope of application. Similarly as the modeling about time based on Allen's principles in CRM or FORT model [19, 20], we propose to use high level relations to express systematically and consistently the spatial relations between heterogeneous entities that compose space. For that purpose, we choose to analyze the compatibility and the possible alignment between the RCC8 and the CIDOC CRM base model.

4. Results

The results of this work are twofold: first, the analysis of the CIDOC CRM properties in regard with the RCC8 topological model. Second, the consistency of the modeling is validated against a sample of Notre-Dame de Paris' data.

We showed that RCC8 relations are compatible with the heterogeneity of the spatial entities in cultural heritage built works. We present a survey and analysis of the direct properties of the CIDOC CRM model in regards to the RCC8 model to highlight the expressivity of the CRM base model [Table 2]. This survey is grouped by the domains and ranges of the properties: it

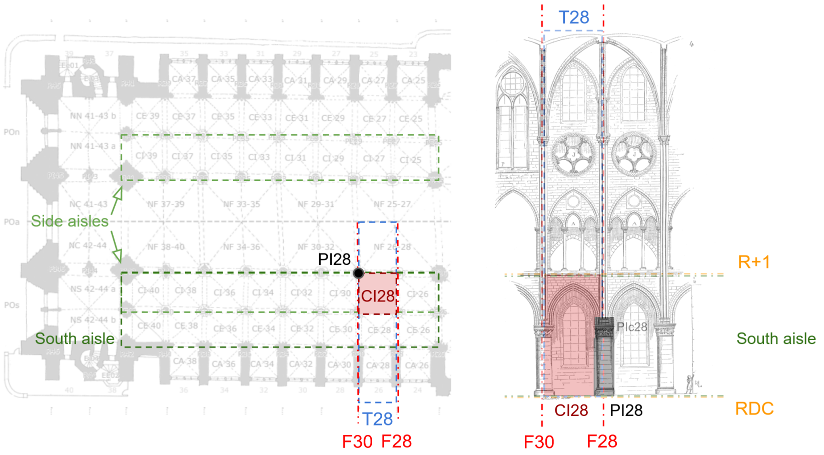

Figure 6: Example of spaces mereotopologically related within the Notre-Dame de Paris cathedral showing the *collatéral intérieur* 28 [CI28] / *interior side of the aisle* 28. It is a portion of space in relation with: *files* (fr)/ *axes* (en) [F28] and [F30], *travée* (fr)/ *span* (en) [T28], and *niveaux* (fr)/ *storeys* (en) [RDC].

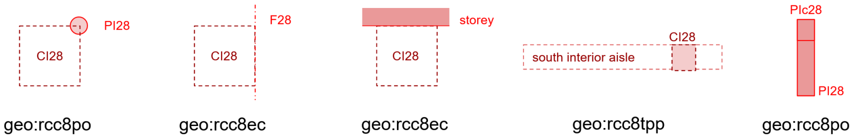

Figure 7: Array of spatial relations expressed using the geoSPARQL RCC8 model between heterogeneous spatial entities with the example presented in [Figure 6] and [Table 2]

shows that spatial properties link few dedicated classes in the CRM model: E18 Physical Thing, E53 Place, E94 Space Primitive and E92 SpaceTime Volume classes. Only E92 and E53 disposes of self-referential properties, E53 is both linked with E18 and E94, E92 is isolated from the other ones. The resulting 4 classes reflect the heterogeneity of elements that we posited in our initial definition of space.

The scope of CIDOC CRM is sufficient in most cases [Figure 3]. More comprehensive cases can arise with cultural heritage built works: we present a sample from Notre-Dame de Paris cathedral data that illustrates this spatial complexity that comes from both the array of spatial entities and their mereo-topological relations. As a representative sample, it features a *collatéral* (fr) / *side-aisle* (en) [CI28] as an empty space 3-dimensional region, two *files* (fr) / *axes* (en) [F28, F30] as abstract 2-dimensional regions, one *travée* (fr.) / *span* (en) [T28] and two *niveaux* (fr) / *storeys* (en) as abstract 3-dimensional region, building elements *pile intérieure* (fr) / *interior column* (en) [PI28] and its *chapiteau* (fr) / *capital* (en) [PIc28] physical as 3-dimensional regions [Figure 6]. This data sample shows the array of spatial relations considered: mereological and topological between place-place, place/object and object/object [Figure 7].

This example is a proof of concept for consistent modeling of abstract spatial relations about built work entities. The aforementioned analysis prevents us from propagating the initial heterogeneity of CRM spatial entities and properties to the application profile. The CRMgeo extension provides an in-between for CRM and geoSPARQL that allows us to reach the RCC8 model in geoSPARQL. The sample data and model is available at: https://gitlab.huma-num.fr/gt-cidoc-crm/architecture-and-built-works-abcrm

5. Conclusion

This contribution was initiated from the case study of Notre-Dame de Paris: the information about space is crucial in the data integration. While in CH datasets, the information about space is mostly homogeneous, the Notre-Dame's spatial data range from microscopic (ie. sample location) to the scale of an object (ie. a built element), a portion of space, or part of the cathedral. The scale of the considered spatial objects depends on the type of research question, method, analysis that are relevant for the dataset. Thus, this range in scale can be seen as a different level of detail in spatial indexing. This led us to go beyond the expression of space as its geometrical representation. We explored specifically abstract spatial relations as a transversal component for archeological, restoration, and analysis data. The proposed modeling with RCC8 and CIDOC CRM is checked against a sample of data representing mereo-topological relations between architectural spaces and built components for a span with collateral and sexpartite vault of the nave in Notre-Dame de Paris. This subset dataset is used as a proof-of-concept that illustrates the conceptual modeling as hybridization/composition between models. The exploration is carried out using an ontological analysis of CIDOC CRM, CRMgeo, geoSPARQL (OGC standard) focusing on the semantics about space, but not about its geometry. The mereological and topological relations in the spaces of a built work, as expressed in 2D (plan), but also as volumes in 3 dimensions and nomenclature.

This article proposed a conceptualization of space from an anthropological perspective of the lived space. Architecture and space are considered as an experienced built environment and thus a primordial substrate of material culture. From an operational viewpoint, the modeling of space as a transversal component enables further operational investigation: interlinking the dense spatialised information as a network, the organization of the perceived space, description of engineering system boundaries (ie. thermics, mechanical analysis) and the alignment of expert systems. The application of this modeling showed its usefulness to the spaces of the cathedral of Notre-Dame but can be transferred to any built environment and architecture.

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