

Semantic models and services for conservation and restoration of cultural heritage: a comprehensive survey

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Abstract. Over the last decade, the Cultural Heritage (CH) domain has gradually adopted Semantic Web (SW) technologies for organizing information and for tackling interoperability issues. Several semantic models have been proposed which accommodate essential aspects of information management: retrieval, integration, reuse and sharing. In this context, the CH subdomain of Conservation and Restoration (CnR) exhibits an increasing interest in SW technologies, in an attempt to effectively handle the highly heterogeneous and often secluded CnR information. This paper investigates semantic models relevant to the CnR knowledge domain. The scope, development methodology, conceptualization aspects and expressive features of each model are described and discussed. Furthermore, the deployment of each model as part of a SW system is examined, with focus on the types and variety of services provided to support the CnR professional. Through this study, the following research questions are investigated: To what extent the various aspects of CnR are covered by existing CnR models? To what extent existing CnR models incorporate models of the broader CH domain and of relevant disciplines (e.g., Chemistry)? In what ways and to what extent services built upon the reviewed models facilitate CnR professionals in their various tasks? Finally, based on the findings, fields of interest that merit further investigation are suggested.

Keywords: Ontologies, knowledge representation, Semantic Web, metadata schemata, decision making

1. Introduction

Over the past decade, the *Cultural Heritage* (CH) domain has gradually adopted knowledge representation methods and tools of the *Semantic Web* (SW) for creating formal definitions of terms, providing a common base for structuring and managing cultural data [11]. This practice initially emerged as an efficient way to address semantic interoperability of (commonly heterogeneous) cultural data, addressing the need for unified collection, management and exchange of data between different CH Institutions [55, 71]. Primarily Web Ontologies have been widely adopted by the CH community for representing the domain, in order to achieve data interoperability, as well as to provide platforms and services to efficiently discover and

share domain-specific knowledge between remote interconnected sources [71]. By extension, Web Ontologies have attracted particular attention within the *Conservation and Restoration (CnR) of CH* research community, as a means for representing and sharing knowledge and data.

The primary aim of CnR of tangible CH lies in the maintenance of the physical, aesthetic and historical integrity of *conservation objects*¹ (including objects, monuments and buildings), ensuring preservation and access for present and future generations [48, 62]. For this purpose, a set of procedures are applied which can be classified in four main categories: i) research, ii) investigation, including diagnostic examination and analysis, iii) CnR interventions, including intervention

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¹ *Conservation object* refers to “the object which is worthy of conservation, and not only repair, maintenance, cleaning, or care” [56].

planning, preventive conservation, remedial conservation and restoration and iv) documentation. Documentation, as well as management of documented information, constitute an integral part of CnR which occurs in parallel with all the other CnR procedures [46].

CnR professionals and scientists collect and disseminate information from and to the wider knowledge pool of the CH domain at all the different stages of the CnR process [46]. Practically, they need to accumulate and exchange a wide range of information about diagnosis methods and results, conservation interventions, preventive measures and other related information, in order to reach conclusions, make decisions and eventually conduct the appropriate intervention [25, 62]. However, up to now, CnR actors face the problem of limited means for linking and retrieving information, mainly due to the fact that CnR-related data are usually heterogeneous and often fragmented for a number of reasons. First of all, CnR laboratories record their data in databases isolated from each other, each one developed according to different requirements which stem from the different specializations [58, 62, 75]. Second, CnR data can be found in various forms structured (e.g., in the form of relational databases), semi-structured (XML annotated documents) or unstructured (free texts), and, as such, are not semantically interoperable [62, 75]. Lastly, the CnR domain suffers from significant terminology inconsistency, since domain specialists tend to use specialized terms in diverse ways² [62, 78]. Even though difficult to achieve, data interoperability (syntactic as well as semantic) and exchange is vital for the CnR domain, and SW provides very promising means to tackle the aforementioned issues, paving the way to effective and efficient organization and management of information [62, 75]. In this context, CnR community has proposed interesting solutions which could dramatically change the way conservation experts perceive and utilize CnR information and knowledge.

In response to the increasing interest of the CnR domain in semantic representation methods, this paper reviews the development and deployment of semantic models developed for the CnR domain. The gathered works include mainly (but not exclusively) formal ontologies. The scope and development methodology of each model are described, while the fundamental aspects and expressive features of the underlying con-

ceptualization are highlighted. Furthermore, the deployment of each model as part of a SW system is examined, with focus on the types and variety of services provided to support the CnR professional. Based on the study, the following research questions are investigated: (a) To what extent the various aspects of CnR are covered by existing CnR models? (b) To what extent existing CnR models incorporate models of the broader CH domain and of relevant disciplines (e.g. Chemistry)? and (c) In what ways and to what extent services built upon the reviewed models facilitate CnR professionals in their various tasks?

The remainder of the paper is structured as follows. In Section 2, the methodology of the survey is discussed. In Section 3, each reviewed work is presented, based on a set of predefined axes (scope, development, structure, deployment). The paper concludes with a discussion that summarizes interesting observations over the reviewed models as well as paths that merit further research, towards a more active and well-rounded support of the CnR process.

2. Methodology

The current survey spans from 2011, when the first attempts are dated, up to today³. As mentioned, the objective of the current review is to study semantic models that have been developed and deployed in the context of the CnR domain. Discovered works were included in the survey according to a set of predefined criteria. Specifically, all works presented in the current survey:

- i) propose models within the CnR domain
- ii) propose models that have been developed using SW technologies and methods
- iii) present some kind of deployment of the proposed model as part of a SW system or service.

It should be noted that it was out of our interest to include works that reuse already existing models, that is without any extension or other modification, in order to essentially perform data modelling. Though we recognize the importance of these projects (e.g., 59, 79), we meant to focus on works that have contributed to modelling (at some extent) of the knowledge domain using SW technologies and methods.

In terms of coverage, the models were reviewed according to a set of *conceptualization aspects* which reflect the basic types of CnR information [54]:

² As [78] mention the term *fresco* may refer to both i) wall paintings in general and ii) wall paintings produced by painting on fresh lime plaster, in different European countries.

³ The data sources of our research include *Semantic Scholar*, *Springer Link*, *Science Direct* and *AATA Online*.

- *administration*, which refers to descriptive information about the conservation object, such as identification information (accession number, title, creator etc.) and information regarding the object's ownership, preservation and management (date of action, location of action, involved stakeholders etc.).
- *materials & technology*, which refers to i) production materials and techniques and ii) structural layers and components of the conservation object.
- *alteration*, which refers to causes (e.g. radiation), processes (e.g. photooxidation) and effects (e.g. peeling) of the conservation object's deterioration.
- *investigation*, which refers to a variety of activities aiming to the acquisition of information either directly from the conservation object and its environment or from other sources (e.g. bibliography, experiments), for the purpose of condition assessment, alteration diagnosis and eventually determining intervention requirements.
- *intervention*, which refers to planning and implementation of actions in order to i) prevent future deterioration of the conservation object (preventive conservation), ii) ensure the long-term safe-keeping of conservation objects (remedial conservation) or iii) make changes to the conservation object so that it optimally approximates its original state or other previous state (restoration).

3. Models Review

Based on the criteria presented in the previous section, 10 works were identified, which were gathered, studied and discussed in juxtaposition. The presentation of the reviewed works follows a chronological order (oldest first). In case of multiple publications on the same work, the initial publication is taken into account in the ordering. Each work has been reviewed and is presented here according to 4 study axes: i) scope and context of the project, ii) development of the proposed model, iii) structure, CnR aspects and expressive features of the proposed model, iv) deployment of the proposed model as part of a SW system or service.

3.1. Ontology of Paintings and Preservation of Art

Twentieth Century in Paint Project (20thCPaint) explored the preservation of 20th c. paintings in Asia and the Pacific. In this context, [35] proposed the *Ontology of Paintings and Preservation of Art* (OPPRA), a semantic model specialized in CnR of movable CH. Key objective of the project was the development of an online knowledge base based on the proposed model that i) allows painting conservators to access integrated and structured information about conservation of 20th c. paintings and ii) facilitates information exchange between painting conservators and other preservation experts⁴. OPPRA provides a machine-readable, formal representation of knowledge about i) material analysis, ii) experiments of damaging processes and potential treatments and iii) applied conservation treatments. The ontology was developed in order to: i) capture CnR documentation data, ii) capture data from published papers and iii) integrate the aforementioned data that derive from both internal and external data sources so that reasoning can be performed over them.

According to [64], the development of OPPRA was organized in five stages: i) description and modelling of the information (classes, properties and relationships) of relevance to painting conservators, ii) combination and reuse of existing models and metadata standards related to a) CH domain, namely *International Committee for Documentation Conceptual Reference Model* (CIDOC CRM) [17], b) physical and chemical properties of materials, namely *OreChem* model [43], and c) resource aggregation, namely *Open Archives Initiative Object Re-use and Exchange* standard (OAI-ORE) [42], iii) reuse of existing controlled vocabularies about a) deterioration mechanisms and preservation methods, namely *Getty Art and Architecture Thesaurus* (AAT) [31] and *Visual Glossary* of the Australian Institute for the Conservation of Cultural Material (AICCM) [3], b) artistic techniques, namely AAT and *International Network for the Conservation of Contemporary Art Database for Artists' Archive* (INCCA) [64] and c) materials and chemicals, namely *RUG Spectral Database* (from now on RUG) [37], *Conservation and Art Materials Encyclopedia Online* (CAMEO) [51] and *US National Institute of Standards and Technology Chemistry WebBook* (from now on NIST) [63], iv) extension and refinement of the introduced classes and relationships, v) evaluation of ontology applicability to the required services within the

⁴ Other preservation experts are curators, materials scientists, chemists, characterization experts and information scientists.

context of the 20thCPaint Project. The model was implemented in *Web Ontology Language Description Logics*⁵ (OWL DL) using *Protégé*⁶ software (for further information see [57]), while *Web Ontology Language* 2⁷ (OWL 2) rules (for painting conservation) were introduced using the *OWL 2 Rule Language* (OWL 2 RL) profile⁸ (implemented in OWLIM (current GraphDB)⁹ *OpenRDF Sesame* triple store¹⁰).

OPPRA classes and relations model information related to the following thematic clusters [64]: i) *Painting*, which represents the identity of the conservation object (e.g., title, artist, period, technique, genre, condition, owner, custodian, provenance), ii) *Paint*, which represents the production material(s) and technique(s) of the conservation object (e.g., paint name, type, chemical property, physical property, pigment, additive), iii) *Paint Decomposition*, which represents alterations of the conservation object (e.g., type, cause, physical/chemical process/reaction), iv) *Paint Analysis Method*, which represents the analysis of the conservation object (e.g., SEM, TEM, FTIR, Raman), v) *Paint Conservation/Preservation Treatment*, which represents the remedial or preventive conservation of the conservation object (e.g., cleaning, environmental conditions control), vi) *Experiment*, which represents experiments that either simulate a damaging process or test a potential conservation treatment, vii) *Publications*, which represents published works related to CnR processes, experiments, and case studies. The combination of classes from different thematic clusters presents some interesting features:

- The materials of paintings can be described using the imported class of CIDOC CRM *E57_Material*, as well as imported classes and relations of the OreChem model (e.g., *ChemicalCompound hasElement ChemicalElement*). This combination aims to be a representation that is both understandable for conservators and consistent for the *Material Science* and/or *Chemistry* community.
- Experimental processes can be described combining several classes and relations that represent the experiment's content, the date, the location, the instruments, the mock sample¹¹ of the exper-

iment, the experimental parameters (e.g., temperature) etc. In case that a mock sample has been further analyzed after its experimental processing (e.g., exposure to a certain temperature), the conducted analysis can be described as well. Eventually, the mock sample can be related to information about its production, experimental processing, analysis and analysis results (process and characterization data).

- Experimental data can be correlated with the published papers that present them, combining classes and relations about conducted experiments and publications.

Based on OPPRA, 20thCPaint project developed a system that consists of an online knowledge base and intelligent services, specialized in CnR and *Conservation Science* (CS)¹² [64]. The system allows the import of documentation and description of experiments conducted by conservators and material scientists, and the uploading of the experimental data to the knowledge base. Furthermore, it allows automatic extraction of structured data about past research and experiments from publications and websites that are relevant to art conservation. The extracted data from published papers are integrated into the knowledge base, together with data from external databases, allowing their linking to the imported user data and consequently a seamless unified search over critical information about conservation, art history and materials science. The semantic search is based on the underlying SPARQL service (that converts users' queries to SPARQL queries) exploits data derived from internal databases (such as *Sidney Nolan Paint Archive*), unstructured information from past publications and external databases (such as CAMEO), enabling conservation-related querying (such as "*What solvents will remove surface varnish from the painting Epiphany?*").

3.2. Monument Damage Ontology

[8] presents one of the prime works proposing a semantic model that covers the CnR of immovable CH as an outcome of MONDIS Project. The main objective of the MONDIS Project was the development of *Monument Damage Information System* (MONDIS), a

⁵ <https://www.w3.org/TR/owl-guide/>

⁶ <https://protege.stanford.edu/>

⁷ <https://www.w3.org/TR/owl2-overview/>

⁸ <https://www.w3.org/TR/owl2-profiles/>

⁹ <https://www.w3.org/2001/sw/wiki/Owlim>

¹⁰ <https://www.w3.org/2001/sw/wiki/Sesame>

¹¹ A sample that simulates the composition and aging of an original painting layer.

¹² CS is defined as the "*interdisciplinary study of the maintenance, care, and protection of art, architecture, and other cultural works*" [5]. As mentioned in [56], CS is commonly referred to sciences of chemistry, physics and biology.

knowledge-based system dedicated to damage diagnosis and possible conservation interventions of historical buildings [12]. MONDIS developed *Monument Damage Ontology* (MDO) in order to efficiently integrate, organize and process diverse information related to the domain of interest, and eventually support documentation and monitoring of historical buildings damages, as well as potential intervention planning/application [14].

The development of the ontology was organized in three phases [12]: i) distinguishing the requirements of damage documentation according to literature and international standards, ii) establishment of the relations among damage factors based on CnR methodologies and workflows, iii) testing the validity of each section of the ontology at public workshops and internal meetings. Existing taxonomies, thesauri and glossaries, such as *International Database and Gallery of Structures* (from now on IDGS) [72], *Material and component classification from StruFail* (from now on MCCS) [26], *Taxonomy of Building Components for Performance-Based Earthquake Engineering* (from now on TBCPBEE) [69], *RTS: Tridnik stavebnich konstrukci a prací* (RTS) [8], *ICOMOS illustrated glossary on stone deterioration patterns* (from now on ICOMOS) [76], *On Site For Masonry Standard Damage Catalogue and List of Structural Typologies and Related Requirements* (from now on OSM) [8], were partially or fully integrated in the model. The model was implemented in OWL 2.

MDO consists of two parts: i) the core, which represents knowledge regarding damages of immovable CH and ii) special taxonomies which provide particular vocabularies for the documentation and analysis of damages [8]. These taxonomies provide an internal organization of specialized terminology for each class. The core part of MDO is further divided in five thematic clusters [8, 13]: i) *Component and Construction Description*, which represents the physical and functional characteristics of a conservation object ii) *Events*, which represents occurrences that can influence the condition of a conservation object, iii) *Damage Diagnosis and Intervention*, which represents alteration processes that affect a conservation object, as well as remedial or preventive conservation and restoration activities that confront the alteration processes and their effects, iv) *Risk Assessment*, which represents the analysis of a potential event or effect that can potentially harm a conservation object, v) *Measurement Assessment*, which represents the measurement of the magnitude of alteration factors and effects. The combination of classes from different thematic clusters presents some interesting expressive features:

- The structural and functional evolution of the monument in the course of time (e.g., the addition of a component after a monument's initial creation) can be described using sub-classes of the *Event* class combined with classes describing the components and construction of the monument.
- The alteration logical scheme of a diagnosis can be described using classes from the *Events* and *Damage Diagnosis and Intervention* clusters: events can trigger damaging processes which in turn generate a tangible and detectable damage (*ManifestationOfDamage*) such as cracks, deflection, loss of material etc.
- A particular damage can be expressed either as a cause or a result in different damaging processes. For example, an *Action* triggers a *Mechanism* and produces *ManifestationOfDamage*, while *ManifestationOfDamage* may act furthermore as an *Action* that triggers a new *Mechanism* with a new result.

Based on the MDO, MONDIS knowledge-based system provides a set of tools for data import, editing, integration, processing and visualisation [14]. More specifically MONDIS includes the inputting applications i) MONDIS mobile/desktop app and ii) Ontomind profile, as well as the visualizing and supporting tools iii) MONDIS explorer, iv) knowledge matrix and v) terminology editor. MONDIS application allows the documentation (on-site for the mobile version) of the condition of historical buildings based on measurements and observations about examined damages [13-14]. The data are uploaded to the MONDIS server, and after being validated they become accessible through the MONDIS explorer. Once shown in the MONDIS explorer records can be integrated with extra information which was not collected and documented during the on-site examination of a building, via Ontomind profile. Ontomind visualizes the ontological mapping of records to the MDO as a simple tree-like structure. The extra information, which can be integrated with the main record, may refer to the structure and evolution of the building, some laboratory testing of its materials, the diagnosis or even proposed treatment of its damages. The records available in the MONDIS explorer are semantically linked to their diagnosis and possible interventions which are visualized and presented to the user through knowledge-matrix web-based application. Therefore, there is a direct correlation between causes, damages and interventions, with further explanation and definitions that an expert or student of CnR domain could

consult. Finally, MONDIS terminology editor facilitates the browsing or editing of the taxonomies and term lists used in MONDIS software tools.

3.3. Color and Space in Cultural Heritage Knowledge Representation

The *Color and Space in Cultural Heritage*¹³ (COSCH) project aimed to enhance the mutual understanding of tangible CH documentation between the various experts of CnR and *Preservation*¹⁴ of CH domain [10]. An important outcome of COSCH community research is *COSCH Knowledge Representation* (COSCH^{kr}), a semantic model that covers an important part of CnR of tangible CH domain: visual documentation and analysis with non-invasive techniques. The main objective of COSCH^{kr} is to facilitate the exchange of interests, needs, capabilities, constraints, limits and perspectives between scientists, technicians and heritage specialists. COSCH^{kr} represents knowledge about spatial and spectral technologies and data, CH objects and CH applications, in order to recommend documentation/analysis strategies for CH objects and applications. COSCH^{kr} also serves as the knowledge base of a system that simplifies communication between technical experts in documentation and experts in CnR and analysis.

COSCH^{kr} was developed in OWL 2, based on an iterative process where the gathered knowledge was first verified by groups of experts [38, 77]. A core group worked on the collection, management and structure of knowledge, derived from relevant expert groups, and the definition of a common vocabulary. Initially, the core group performed a survey using questionnaires in order to structure the content, to define work areas through the determination of relevant terms and vocabularies, and to identify contact persons having a specific expertise and being available for discussions and feedback. Thereafter, experts participated in discussions over three representative case studies, contributing to the development of class structure and dependencies as well as the inference rules. In order to maintain information interoperability, the intention was to keep the ontology in line with CIDOC CRM.

The taxonomical hierarchy of COSCH^{kr} has on average five levels, while the entire ontology contains more than 750 classes [77]. The top-level structure of

COSCH^{kr} consists of five classes interrelated through five properties [10]: i) *Physical Thing*, which represents a conservation object to be measured, ii) *CH Applications*, which represents cultural heritage research questions applying to spectral or spatial data, iii) *Data*, which represents digital/analogue data and document types that are either generated or used to process existing/generated data, iv) *Technologies*, which represents technical processes, measurement principles, tools/instruments and the way they are set up to generate or process data, and v) *External Influences*, which represents limitations of a documentation/analysis project (in terms of location, budget, environmental conditions etc.). COSCH^{kr} subclasses are associated with inference rules, which cut across the top-level classes (e.g., *Revelation of Underdrawing* (subclass of *CHApplications*) has *Requirement 2D_Data* (subclass of *Data*)). The combination of classes from different levels presents some interesting features:

- Objects can be described using the class *CompositeObjects*, since they are perceived as complex structures of different materials that have different physical and optical characteristics. COSCH^{kr} does not define objects as their real world counterparts (e.g., church is not represented by class “Church”).
- The purpose and data requirements of a documentation/analysis action and its corresponding technology can be described using the classes *CHApplications*, *Data* and *Technologies*: the purpose of the action determines the requirements of the nature and quality of data, while data of particular nature and quality can be generated by particular technologies.

Based on COSCH^{kr}, the COSCH project proposed a system, the COSCH^{kr} platform, that enables experts from different subdomains of CnR and *Preservation* of tangible CH to put forward their queries and get answers related to documentation/analysis strategies for CH objects and applications without worrying about the complexity of the backend model [38]. Particularly, the proposed system would allow seeking answers to queries of varying complexity and invokes the model to infer underlying facts and heuristics. First of all, the system aims to help users to identify useful factors for different documentation/analysis actions as well as factors that cannot be satisfied, using implicit

¹³ COSCH is the *COST-Action TD 1201*.

¹⁴ *Preservation* is defined as “the protection of cultural property through activities that minimize chemical and physical deterioration and damage and that prevent loss of informational content” [4].

reasoning. Afterwards, based on those factors, the proposed system would be able to recommend solutions, providing experts with an overview of optimal spectral and spatial recording strategies according to their needs.

3.4. DOC-CULTURE

The DOC-CULTURE project (Development of an integrated information environment for assessment and documentation of conservation interventions to cultural works/objects with nondestructive testing techniques) explored non-destructive testing and evaluation techniques (NDT&E) in three axes: i) the NDT&E usage in assessment of conservation object condition and conservation interventions effects, ii) the documentation of NDT&E data through metadata and conceptual frameworks and iii) the implementation of an information system for the recording and storage of NDT&E data [39-40]. In this context [40] and [73] propose a CIDOC CRM extension for facilitating the complete representation of the field of NDT&E.

In order to develop the CIDOC CRM extension, first, the intended user groups of the system, the requirements regarding information documentation and the different CnR processes and stages (including NDT&E techniques) were defined [40, 73]. In this context, the main entities and properties of NDT&E were identified. Next, different standards for modelling data related to the CH domain were studied. Eventually, CIDOC CRM and Dublin Core (DC) were employed for the representation of DOC-CULTURE entities and properties. In addition to DC, the elements of the Metadata Object Description Schema (MODS), Resource Description and Access (RDA), PREMIS and Muse Meta metadata standards were employed for data modelling. Based on this study, a set of CIDOC CRM and DC classes and properties that can be used for modelling the domain of interest was identified, while CIDOC CRM classes that should be extended in order to better represent the NDT&E field were proposed [40].

The DOC-CULTURE model has five main entities [73]: i) Object, which represents the conservation object, ii) Conservation, which represents CnR interventions, iii) Measurement, which represents measurement actions, iv) Equipment, which represents equipment used for CnR and measurement actions and v) Digital Documentation, which represents both the digital representation of the conservation object (e.g., digital images) and any digital file produced during CnR

or measurement actions. The five main entities and their properties are represented by classes and properties of CIDOC CRM and DC. Furthermore, CIDOC CRM entities were extended with the DOC-CULTURE classes: i) Conservation Activity, which represents CnR processes applied on artifacts, ii) Frequency, which represents the frequency of an event occurrence. The combination of DOC-CULTURE classes presents some interesting features:

- The DOC-CULTURE class *E91_Conservation_Activity* and its subclasses represent the various processes that can be applied on a conservation object - from examination and analysis to intervention. Interventions may include past interventions that have been applied on the conservation object.
- It is possible to describe that a measurement assesses a past intervention, and that the assessment output is recorded in a document or an image.

The proposed model has been used for modelling data related to conservation interventions of the National Archaeological Museum of Athens. Additionally, the model has been deployed in an information system built for the purposes of the DOC-CULTURE project. The system consists of the following sub-systems, which provide the respective services [41]: i) image processing, which allows the application of filters on images of conservation objects, ii) numerical analysis, which provides functions for the identification of past conservation processes and detects lesions on the surface of a conservation object, iii) metadata management, which allows the matching of metadata elements to database columns, iv) image annotation, which enables the addition of annotation marks on an image together with information about previous CnR processes and v) documentation management functionality, which implements the proposed metadata scheme as well as the documentation process conducted by CnR experts.

3.5. Ontology for Degradation Phenomena and Annotation on 3D Reconstructions

[49] presents a correlation pipeline for the integration of the three dimensions of a masonry structure: i) semantic dimension, which refers to concepts used by experts in order to describe conservation state, ii) spatial dimension, which refers to spatialized annotations on 3D representations, iii) morphological dimension, which refers to morphological descriptors (e.g., occlusion, curvature, roughness) of annotated regions of 3D

representations. The pipeline uses an ontology for recording and integrating multidisciplinary observations of the conservation state of masonry structures, spatialized into a *reality-based 3D* representation¹⁵.

The ontology (from now on ODPa-3DR) was developed based on *Lassila's method* [45] using *Protégé* software [50]. The development of the ontology had to meet the requirements of semantic annotation. Therefore, four thematic description concepts were defined in order to represent the conservation state of a masonry structure [50]: i) *Material*, ii) *Building technique*, iii) *Architectural components* and iv) *Degradation phenomena*. Different thesauri were built for the different description concepts, based on the terms that have been collected from experts and specialized glossaries (namely *ICOMOS illustrated glossary on stone deterioration patterns* and *Architecture: méthode et vocabulaire* (from now on ARC) [65]). To align the ontology with the wider CH domain, some of the ontology's classes were mapped to CIDOC CRM and related compatible models (CRMsci [22], CRMdig [19] and CRMinf [21]).

ODPa-3DR, combined with CIDOC CRM and CIDOC CRM compatible models, represents knowledge related to the following axes [50]: i) *Argumentation*, which represents the study and reasoning over a conservation object, ii) *Information*, which represents documents and digital files about a conservation object iii) *Region*, which represents a specific area on a conservation object, iv) *Description Concepts*, which represents material(s), building technique(s), architectural components and degradation phenomena of an area under study, v) *Digital Acquisition*, which represents the digitization of a conservation object. The combination of CIDOC CRM and its compatible models, as well as the introduced classes, present some interesting features:

- Materials and technique of a masonry structure as well as its alterations can be described using the *DescriptionConcept* class (e.g., *Architectural-Component shapeByUsing BuildingTechnique*, *BuildingTechnique hasMaterial Material*).
- A spatialized region can be correlated with one or more description layers using the CRMdig *D35_Area* class and the introduced *Description-Concept* class (e.g., a particular region on a wall is constructed by a particular building technique and presents the alteration of spalling).

ODPa-3DR is deployed in a system for *reality-based 3D* semantic annotations of masonry structures'

conservation states [49-50]. The basic functionality of the system is as follows: The user inputs a set of digital images of a physical object, and marks 2D regions on these images. Based on the marks, the system extracts spatial relationships (by 2D-to-3D-to-2D projection), as well as morphological features (by morphological analysis). Then, the system allows the assignment of description concepts of different thematic layers on the marked regions. Finally, the user indicates references and/or resources that justify the annotation that he/she has done. With this process it is possible to manually annotate the alteration of a wall on a 2D image and use the corresponded 3D point cloud to compute the material loss descriptor of this particular region of the wall. Then, each 2D annotation linked to the thematic layer of the degradation phenomena of the ontology, recovers a "material loss" value coming from the 3D point cloud analysis.

3.6. CRMcr

Patrimoine culturel et Restauration-Conservation: Ontologies pour l' Usage d' un Referentiel commun aux différentes Sources de données (PARCOURS) project followed an ontology-driven approach in order to i) address the interoperability problem of CnR data provided by different CH Institutes, and ii) develop a common infrastructure for the semantic retrieval of integrated CnR data [60]. In this context, [60] proposed the CRMcr, a semantic model of CnR of tangible CH. CRMcr is an extension of the CIDOC CRM and it provides a unified understanding of CnR data.

The development of CRMcr started with the definition of a core structure and the main CnR requirements of the ontology [7]. During this process scientists and domain experts of the CnR field were involved. Next, a set of sample data structures and example data related to the CnR processes was mapped to different CH domain ontologies (including *Europeana Data Model* (EDM) [16], ABC [23]). CIDOC CRM was considered as the most appropriate choice for CnR data modelling. As such, CRMcr was developed as a CIDOC CRM extension. Additionally, a layered ontology architecture was proposed, combining CIDOC CRM, the CRMsci compatible model, the CRMcr extension for CnR domain and several more specialized thesauri. The use of thesauri tackled the problem of inconsistency among different CnR terms, at both the syntactic and semantic level. Most of the thesauri were built during the PARCOURS project, were managed

¹⁵ *Reality-based 3D* is the technique used to create a three-dimensional representation of a real object [50].

by the *Thesaurus Management System* (TMS) *Gestion Informatisée de Nomenclatures Collaboratives et Ouvertes*¹⁶ (GINCO), and were integrated into the CRMcr model.

CRMcr consists of i) 93 concepts and 82 relationships of CIDOC CRM ontology, ii) 22 concepts and 24 relationships of CRMsci and iii) 63 new concepts and 27 new relationships. The new concepts specialize at least one concept from CIDOC CRM or CRMsci. CIDOC CRM classes and relations are used to represent identification of events and objects. CRMsci classes and relations are used to represent scientific observations and measurements. The new concepts and relations of CRMcr represent knowledge related to i) Conservation Object, which represents the identification and physical features of a conservation object, ii) Events, which represents alterations, scientific studies, documentation, and intervention activities of a conservation object, iii) Instruments and Techniques, which represents the equipment used during the various processes (e.g. production, investigation, intervention), and iv) Results, which represents data produced by scientific studies [7]. The combination of classes presents some interesting features:

- It is possible to describe how different events interact with each other using some of the semantic relations of CRMcr extension. For example, the CRMcr object property *R17_detected* relationship correlates an alteration event with the activity of scientific study that detected it.
- Degrading events that affect the condition of the object, as well as the exact affected region of the object can be described using the class of CRMsci *S18_Alteration* and the classes of CRMcr *C14_Alteration_Factor* and *C15_Altered_Area*.
- Measurements or experimental analysis can be described using CRMsci classes (such as *S3_Measurement_by_Sampling*) and/or more specialized CRMcr classes for non-invasive processes (such as *C19_Scientific_Imagery*).
- CnR interventions can be described using the CRMcr classes *C22_Intervention*, *C23_Conservation*, *C24_Restoration* and a list of specific interventions validated by the domain experts and following the terminology specified by the International Council of Museums - Committee for Conservation (ICOM-CC).

In the context of the PARCOURS project, a data integration system for the CnR domain was developed

based on CRMcr, providing search and retrieval services [61-62]. The PARCOURS system follows a mediator approach in order to tackle restrictions imposed by CH Institutions, and allows them to keep managing their repositories autonomously. In particular, all data sources involved in the integration process refer to the CRMcr ontology, which is used as the mediator model. During the retrieval process, the system interacts simultaneously with the different databases regarding a query and retrieves details concerning both the physical characteristics of the queried cultural object (e.g., location, authors) and the occurred events (e.g., type of event, used techniques, measurements, actors). Moreover, the system provides a keyword-querying interface, where the thesauri of CRMcr are used as referential guidelines, allowing the user to choose relevant terms for submitting a request.

3.7. Cultural Heritage Artifact Partonomy

By exploiting semantic technologies and knowledge organization systems, the GRAVITATE project developed the GRAVITATE platform which provides tools that exploit SW technologies in order to annotate and analyze 3D models of artefacts, as well as to retrieve semantic data related to the artefacts [66]. In this way GRAVITATE platform benefits archaeological and conservation study of CH artefacts. An important outcome of the GRAVITATE project and an integral part of GRAVITATE platform is the *Cultural Heritage Artefact Partonomy* (CHAP) hierarchy. As its name suggests, CHAP constitutes a *meronymy* and supports archaeological search of i) documentation of artefacts, as well as of individual artefact fragments or groups of fragments, ii) the part-based annotation of (3D reconstructions of) artefacts (for information retrieval purposes) and iii) computational analysis and comparison of artefacts.

The main classes of CHAP were defined based on an archaeological corpus of texts (i.e. archaeological publications, catalogues, excavation reports) as well as fundamental archeological knowledge [15]. The general structure of the model was edited in *Protégé* software and was modelled as a SKOS hierarchy¹⁷. The CHAP meronymy was then aligned to CIDOC CRM, its compatible model CRMdig, and *Common Shape Ontology* (CSO) [74], creating a semantic scheme suitable for the representation of knowledge about both artefacts and their digital counterparts. CSO was used in order to specify the type of

¹⁶ <http://culturecommunication.github.io/ginco/>

¹⁷ <https://www.w3.org/2004/02/skos/>

geometric representation used to model the digital artefact (e.g., triangular mesh). During the alignment stage, some extra classes and object properties were introduced as extensions of CIDOC CRM and CRMdig.

The CHAP meronymy is organized in five central concepts all related to statues and figurines [15]: i) *Body part*, which represents anatomical constituents and related characteristics (e.g., hairstyle), ii) *Attire*, which represents accessories (e.g., necklace), iii) *Decoration*, which represents figurative decorations and geometric decorations (e.g., flower), iv) *Colour*, which represents coloring, and v) *Technique*, which represents manufacturing techniques. The semantic scheme (a combination of CIDOC CRM, CRMdig, CSO and extra classes based on requirements of the *Gravitate* project), to which CHAP meronymy is aligned, can be divided in two main conceptualization aspects: i) the physical artefact and ii) the digital counterpart of the physical artefact. The CHAP meronymy is included in the first aspect. The CHAP meronymy, in combination with CIDOC CRM and CRMdig, presents some interesting expressive features:

- The duality between the physical artefact and its digital counterpart can be described using the CIDOC CRM class *E22_Man-Made_Object* and the CRMdig class *D1_Digital_Object*.
- The features of the physical artefact can be described using the CIDOC CRM class *E26_Physical_Feature* and the artefact itself can be further defined using concepts from the CHAP hierarchy. The features of the digital representation of the artefact can be described using CRMdig class *D35_Area* and the artefact itself can be further defined using the CSO ontology.
- The computation of complex geometric characteristics (e.g., curvature) can be described using the CRMdig class *D9_Data_Object* and the *ext_chap* object property (which was introduced as part of the extension): *LX_has_quantity* (e.g., *D9_Data_Object ext_chap: LX_has_quantity D9_Data_Object*)

CHAP is deployed in the knowledge base of the GRAVITATE platform and it is exploited by the tools provided by the platform for analysis and annotation of 3D models of artefacts [15, 66]. In particular, the GRAVITATE platform's tools are i) *inspection view*, which facilitates the parallel visualization of different

3D models and geometric properties, ii) *feature recognition*, which provides automatic identification of features on 3D models of artefacts and iii) *annotation mode*, which allows the annotation of areas on 3D models of artifacts. The user can input qualitative and quantitative data about annotated areas, which are stored in the knowledge base of the platform. Data and metadata about artefacts and artefacts' 3D models are stored in the knowledge base and can be retrieved using queries.

3.8. Conservation Process Model

[1] proposes *Conservation Process Model* (CPM), a semantic model specialized in CnR of immovable CH and particularly CnR of historical buildings. CPM's aim is twofold: i) to represent knowledge of CnR processes and ii) to facilitate the integration, mediation and interchange of heterogeneous conservation information, at both the academic and the professional level. Furthermore, in order to provide integration of geometrical and non-geometrical information related to conservation of architectural heritage, CPM has been deployed in *Autodesk Revit*¹⁸, a *building information modelling* (BIM) software¹⁹.

CPM was developed in OWL, using the *Protégé* software, and its structure follows the scheme of CIDOC CRM [1, 27]. Additionally, two extensions of CIDOC CRM, FRBRoo [24] and *AR model* [30], were taken into account in the formalization of CPM. Specialized terms of the *ICOMOS illustrated glossary on stone deterioration patterns* were considered to be mapped on CPM classes related to decay phenomena, in order to provide standardized terminology for decay specification. Several rules were developed in *Semantic Web Rule Language*²⁰ (SWRL) in order to compare assignments resulting from different analyses so as to further verify the results of investigation processes [27].

CPM's classes and relations are organized in five thematic clusters [1]: i) *Artefact*, which represents the architectural structure, ii) *Investigation Process*, which represents the examination and analysis with non-destructive or destructive methods, iii) *Actors*, which represents people related to the building's history or study, iv) *Lifecycle I*, which represents the description and analysis of alterations of materials and

¹⁸ <https://www.autodesk.com/education/free-software/revit>

¹⁹ BIM is an environment that allows the creation of virtual building models, which can be linked to numerical data, texts, im-

ages, and other types of information. It is used in the fields of *Architecture*, *Engineering* and *Construction* (for further information see [68]).

²⁰ <https://www.w3.org/Submission/SWRL/>

structure of buildings and v) *Lifecycle 2*, which represents conservation planning, interventions and general managing processes. The combination of classes from different thematic clusters presents some interesting expressive features:

- Investigation process, which includes investigation method, tool, sample, actor, input and output data, can be described in detail using the respective classes *EcpmP49_Investigation_Method*, *EcpmP50_Investigation_Tool*, *EcpmP112_Investigation_Sample*, *EcpmP90_Information_Object* and CIDOC CRM class *E39_Actor*).
- Decay analysis and the surface under examination can be described using the CIDOC CRM classes *E14_Condition_Assessment* and *E3_Condition_State* and the CPM class *EcpmA241_Surface_Area* class. The subclass of CIDOC CRM *E55_Type* class, *Ecpm2_Decay_Phenomenon*, can be used for the specification of the CIDOC CRM class *E3_Condition_State* (e.g., *E3_Condition_State P2_has_type Ecpm2_Decay_Phenomenon*).

Based on CPM, [1] present an ontology-based *BIM Semantic Bridge* that provides a connection between a BIM-based software database and a knowledge base of conservation data. BIM-based software *Autodesk Revit* was used for the annotation of specific areas of decay or intervention on building models. The combination of *Autodesk Revit* and CPM facilitated geometrical representation of conservation information and by extension the management of the whole CnR process. Furthermore, in a more recent work, [2] propose the combination of CIDOC CRM, CIDOC CRM compatible models CRMba [18], CRMgeo [20], CRMinf and the CPM ontology for representing conservation management of urban buildings, using the *Risk Map of Cultural Heritage* system of *Culture Ministry of Italian Republic* (MiBAC). The main objective of this approach is the description of the buildings, including their main features together with vulnerability and transformation index. The combination of 3D models of the buildings with the semantic representation of risk-related information could provide stable monitoring of the urban tissue, constantly up-to-date with new data deriving from the interventions.

3.9. Polygnosis Thesaurus

[67] proposes *Polygnosis Thesaurus* as part of the *Polygnosis* educational knowledge web platform (*Polygnosis* platform). *Polygnosis Thesaurus* was developed in the context of the *Politismos-Technologia, New Technologies in the Research, Study, Documentation and Access to the Information for Cultural Heritage Objects and Monuments* (POLITEIA) project, and it is not an ontology per se, but has been built based on the ontological model of *Polygnosis* platform. The ontological model of *Polygnosis* platform is based on CIDOC CRM and its compatible models CRMsci and CRMdig. *Polygnosis Thesaurus* aims to facilitate the collaboration of interdisciplinary working groups, in order to retrieve information about optical and laser-based techniques for advanced imaging, analysis and diagnosis of CH objects (movable and immovable CH). For the development of the thesaurus, the authors use an ontology-driven faceted analysis method for the definition of the top-level concepts that consist of the backbone for organizing the knowledge of the thesaurus.

The development of *Polygnosis Thesaurus* commenced with the collection and analysis of scientific sources, terminology and thesauri related to i) conservation and diagnosis of CH objects and ii) laser-based examination techniques [67]. The reused thesauri and vocabularies are AAT, *Network of Research Computer Image Systems in Europe* (NARCISSE) [44], *Conservation & Restoration Institutions for Scientific Terminology dedicated to Art Learning Network* (CRISTAL) [28] and *European Illustrated Glossary of Conservation terms for Wall-Paintings & Architectural Surfaces* (EwaGlos) [78]. Afterwards, the *Polygnosis Thesaurus* structure was specified developed in three steps: i) definition of semantic categories and facets of the thesaurus according to the main concepts of the *Polygnosis* platform model (namely *Method Application*, *Example*, *Technical Examination*, *Objects*, *Data*, *Glossary Terms* and *Publications*), ii) formulation of terms hierarchies and finally iii) definition of semantic relationships between the terms. *Polygnosis Thesaurus* was developed with TMS *THEMaS*²¹. Furthermore, in [67] a mapping is presented between facets of *Polygnosis* and concepts of CIDOC CRM (e.g., *Material Objects* facet maps to *E70_Thing*). The mapping was conducted to ensure a common understanding of terms and concepts by the different scientific communities of CH.

²¹ <https://www.ics.forth.gr/isl/themas-thesaurus-management-system>

Polygnosis Thesaurus is organized in four extensible facets [67]: i) *Material Objects*, which represents things with physical substance that constitute complete units and have a relatively stable form with identifiable boundaries in at least one dimension, ii) *Investigation Methods*, which represents systematic procedures designed to detect, identify and demonstrate *Identifiable Features of Material Objects*, iii) *Identifiable Features*, which represents features that are inextricably linked with *Material Objects* on which they are found (e.g., construction features, deterioration phenomena etc.), and iv) *Data*, which represents digital informational material related to the documentation of *Material Objects* or information objects and other processes of information acquisition and/or production (by recording, by digitization, through study, during intervention etc.). Apart from the organization of IS-A hierarchies, terms are interconnected through additional (non-hierarchical) binary *associative relationships*. The combination of terms from different facets presents some interesting expressive features:

- The objects and the investigation methods that can most effectively examine them can be described using terms of *Material Objects* and *Investigation Methods* facets.
- The objects and the features that are detected and identified on them can be described using the terms of *Material Objects* and *Identifiable Features* facets.
- The application of examination methods and data that are resulted from them can be described using the terms of *Investigation Methods* and *Data* facets.

Polygnosis Thesaurus supports the educational role of the *Polygnosis* platform, by providing relevant terms that the user might not have thought of, thereby facilitating the exploration and disambiguation of information [67]. The *Polygnosis* platform stores and integrates data, collected from scientific examination methodologies and applications that have been conducted in the laboratory of *Photonics for Cultural Heritage of Institute of Electronic Structure and Laser - Foundation of Research and Technology Hellas (IESL-FORTH)*. It captures accumulated knowledge and data regarding diagnostic tools and methodologies, and display cases (the use of tools and application of methodologies to CH objects). In practice, the user (conservator, heritage researcher or practitioner) can select the case that interests him/her either by examination type or evidence type and get descriptive

texts regarding the examination type and evidence selected, as well as a list of related cases on different CH objects.

3.10. *Heritage Resilience Against CLimate Events on Site*

The European project *HERitage Resilience Against CLimate Events on Site* (HERACLES) aimed to develop an ontology-based platform, which provides a knowledge base for the efficient storage and management of data related to i) the impact of climate change on immovable CH and ii) the mitigation of potentially harmful effects [32]. An important output of this research was the HERACLES application ontology, a semantic model which covers the preservation of immovable CH. As such, the primary object of the HERACLES ontology is the efficient integration, exchange and retrieval of data related to climate change impact, which are often unstructured, incompatible or in some cases partial.

The HERACLES ontology was developed following a workshop-based approach, while the *WebGenesis*²² software was used for development [32]. During the workshop, the participants determined requirements for the conceptual representation according to the methodology of [29]. Next, competency questions were formulated in order to specify the area of interest. The participants identified the main subdomains of the ontology, including: i) *Materials*, ii) *Damage*, iii) *Risk Assessment*, iv) *Stakeholders and Roles*, v) *Climate Change Effects*, vi) *Sensors and Measurements* and vii) *Standard Operating Procedures/Guidelines*. Next, classes and their relationships were defined, while descriptions of the classes were added to facilitate human comprehension of the data model. Several sources were used as reference material for the HERACLES ontology, including: i) SWEET ontologies [70], ii) the *Materials Ontology* [6], iii) *Open Geospatial Consortium* (OGC) standards including the *Sensor Things Application Programming Interface* (from now on ST-API) [47] and the *Internet of Things Tasking Capability* (from now on ITTC) [36].

The HERACLES ontology consists of 109 classes, 204 object properties (102 properties plus their inverse), 49 data properties and 141 individuals [33]. The core classes of the ontology are [32-33]: i) *Cultural Heritage*, which represents monumental art and buildings, ii) *Cultural Heritage Properties*, which rep-

²² <https://www.iosb.fraunhofer.de/servlet/is/21107/>

resents characteristics of monumental art and buildings, iii) *Cultural Heritage Element*, which represents components of monumental art and buildings, iv) *Damage and Effect*, which represents changes that occurred on a component of monumental art and buildings due to an event, as well as abiotic factors that induce climate events that in turn cause damages, v) *Material*, which represents materials used in CH management, vi) *Action*, which represents measurements for monitoring, analyzing or preserving monumental art and buildings, vii) *Stakeholders*, which represents actors in CH preservation, viii) *Risk*, which represents the risk of harm of monumental art and buildings and ix) *Location*, which represents spatial information (e.g., the position of a measurement sensor). Combinations of the core classes provide the following expressive features:

- The part of an object from which a measurement takes samples and where a damage occurs can be described using the *Cultural Heritage Element* class. As such, actions, damages or materials can be linked to CH objects using the aforementioned class.
- The effects of climate events, the measurable parameters of these effects and the damages that they cause can be described using the classes *Effect / Effect Type*, *Damage / Damage Type* and *Parameter / Parameter Value*.
- Monitoring measurements, as well as results of simulation models about risk levels can be described and combined using the classes *Measurement*, *Location*, *Sensor*, *Risk* and *Risk Assessment*. Through these classes, the ontology enables the representation of risk assessment and modelling of actual or potential problems.
- The conservation actions and measures taken, as well as suggestions of conservation actions, can be described using the classes *Action* and *Actions Type*. Furthermore, these classes can be linked to damages, representing knowledge about damage mitigation.
- Materials of CH and materials used in conservation actions, as well as their qualitative and quantitative characteristics and purpose (e.g., binder)

can be described using the classes *Material*, *Material Property* and *Material Purpose*. Furthermore, these classes can be linked to actions, representing knowledge about the appropriateness of material usage.

The HERACLES ontology serves as the backbone of the HERACLES knowledge base: every entry in the knowledge base is an instance of the ontology [33]. HERACLES knowledge base collects and integrates multisource information in order to effectively i) provide complete and up-to-date awareness about the conditions occurring in a CH site and ii) support retrieval and decision making for innovative measurements improving CH resilience. Particularly, HERACLES platform provides input forms, through which data are semantically integrated. The input form contains several text fields (e.g., for textual descriptions), while links to other instances can be created through selecting elements from lists. Additionally, an online endpoint is provided to facilitate instance creation/deletion. Regarding presentation of data, for each entry the system provides images and quick links to useful related information (e.g., damages, reports, sensor data). This endpoint is also used by the HERACLES mobile application, which allows reporting of damages on site, by delivering information such as location coordinates and description, as well as pictures, video footage etc. to the HERACLES knowledge base, in order to be presented to the back-end user.

4. Discussion and conclusions

The study of the different representations of CnR knowledge and their deployment in SW-enabled systems and services revealed some interesting points of convergence or divergence, which are discussed in the following sections. The study findings are overviewed in *Table 1* and are organized and discussed according to three axes: i) content, ii) re-use of existing models, iii) deployment.

Table 1

Overview of the reviewed works according to i) content, ii) existing models re-use and iii) deployment.

Model's Name	Content		Re-use of Existing Models			Deployment	
	Object Type	CnR Aspects ²³	Ontologies	Metadata Standards	Terms Lists/Thesauri	Related System	Services ²⁴
OPPRA	Movable CH	ADM, MAT, ALT, INV, INT	CIDOC CRM, OreChem	OAI-ORE	AAT, AICCM, INCCA, RUG, CAMEO, NIST	20thCPaint Platform	INTEG, SEA, ANN
MDO	Immovable CH	ADM, MAT, ALT, INV, INT	-	-	IDGS, TBCEPBE, MCCS, RTS, ICOMOS, OSM	MONDIS	INTEG, SEA, VIS
COSCH ^{KR}	Movable & Immovable CH	MAT, INV	-	-	-	COSCH ^{KR} Platform	REC
DOC-CUL-TURE	Movable CH	ADM, MAT, INV, INT	CIDOC CRM	DC, MODS, RDS, PREMIS, Muse Meta	-	DOC-CUL-TURE Information System	VIS, ANN
ODPA-3DR	Immovable CH	ADM, MAT, ALT, INV	CIDOC CRM, CRMsci, CRMdig, CRMinf	-	ICOMOS, ARC	<i>Reality-based 3D semantic annotation of masonries' conservation state</i>	SEA, VIS, ANN, MOR
CRMcr	Movable & Immovable CH	ADM, MAT, ALT, INV, INT	CIDOC CRM, CRMsci	-	-	PARCOURS System	INTEG, SEA
CHAP	Movable CH	MAT, INV	CIDOC CRM, CRMdig, CSO	-	-	GRAVITATE Platform	SEA, VIS, ANN, MOR, FEA
CPM	Immovable CH	ADM, MAT, ALT, INV, INT	CIDOC CRM, FRBRoo, AR model, CRMsci, CRMdig, CRMinf	-	ICOMOS	<i>Ontology-based BIM Semantic Bridge</i>	INTEG, VIS, ANN
Polygnosis Thesaurus	Movable & Immovable CH	MAT, ALT, INV	CIDOC CRM	-	AAT, NARCISSE, CRISTAL, EwaGlos	Polygnosis Platform	INTEG, SEA
HERACLES	Immovable CH	ADM, MAT, ALT, INV, INT	SWEET, Materials Ontology	OGC, ST-API, ITTC	-	HERACLES Platform	INTEG, SEA, VIS

²³ ADM: administration, MAT: material & technology, ALT: alteration, INV: investigation, INT: intervention²⁴ INTEG: data integration, SEA: semantic search, VIS: visualization, ANN: semantic annotation, MOR: morphological analysis, FEA: feature recognition, REC: recommendation of digitization and analysis methods

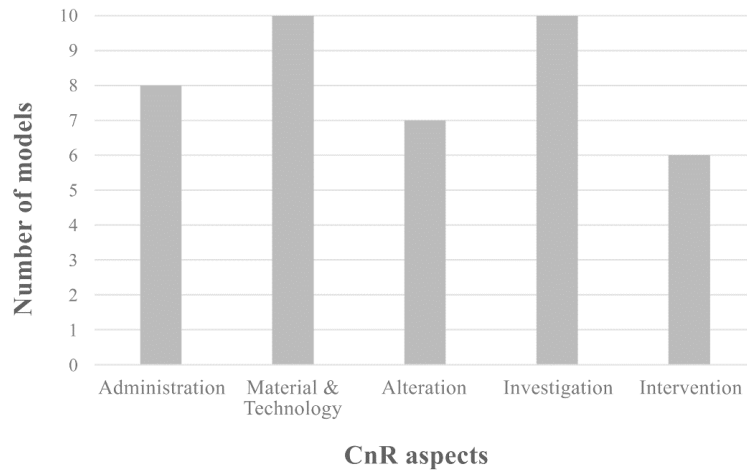


Fig. 1. Coverage of CnR aspects.

4.1. Content

Obviously a common requirement is the modelling of the *conservation object* per se. The majority of the reviewed models are specialized in a certain category of conservation objects: in particular, 4 out of the 10 reviewed models are specialized in immovable CH, while 3 of them are specialized in movable CH; finally, 3 models cover tangible CH in general. An interesting observation is that different models allow different granularities of categorization of a conservation object. For example, the CPM model represents a building (i.e. the conservation object) using classes of specific building types (*EcpmA36_Oratory*), while the COSCH^{KR} model represents a building at a more abstract level, using the class *CompositeObject*. Both representation levels may be handy depending either on the different levels of acquired knowledge (e.g., we may not be certain about the use of a building in order to categorize it as *Oratory*) or different reasoning requirements.

Based on the conceptualization aspects defined in Section 2, *Figure 1* depicts the degree to which the identified CnR aspects are covered by the reviewed models. The *investigation* aspect is covered by all models, which is expected since the main objective of all the reviewed models is organization and management of CnR data, and the investigation stage constitutes the primary means of collecting such data. The expert conducts investigation in order to identify and record the attributes of a conservation object, both material (e.g., structural layers) and non-material (e.g.,

historic value), as well as deduce current and potential preservation issues (e.g., deterioration due to environmental conditions). Knowledge about the conservation object's attributes together with any preservation issues are part of the *alteration* and *structure & materials* aspects, which are covered by the majority of the reviewed models. On the other hand, while the *intervention* aspect is of apparent interest for the CnR domain and it also constitutes an important means of acquiring CnR data, it is only covered by 6 models, which is less than expected (especially compared to the *investigation* aspect).

4.2. Re-use of existing models

While the scope and context of the reviewed works may differ, there is a common interest for providing interoperability of CnR data. Towards that direction, most of the reviewed models were developed either from scratch and were then mapped/aligned to existing ontologies, or they were built entirely by extending existing ontologies (with the exception of MDO and COSCH^{KR}).

Figure 2 summarizes the re-usage of different ontologies, metadata standards, term lists and thesauri by each CnR model. The CIDOC CRM ontology, as well as its compatible models, were largely adopted by the majority of the projects. Additionally, specialized ontologies from other knowledge domains relevant to CnR were adopted for the development of the models. Most of the works took into account and adopted ontologies from the fields of Architecture (*AR model* was adopted by *CPM*), Chemistry and Material Science

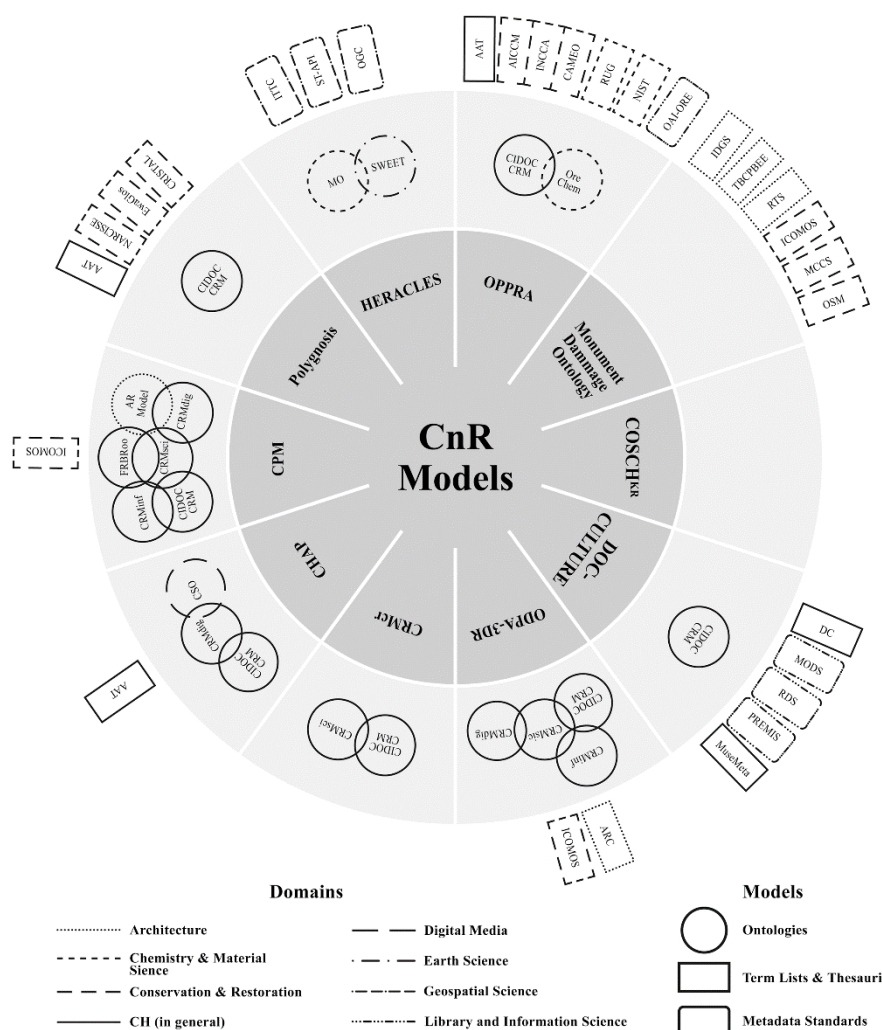


Fig. 2. Re-use of existing models of i) ontologies (circles), ii) metadata standards (curvy rectangles) and iii) term lists & thesauri (rectangles) by each CnR model (the different shape outlines denote the different domains that the reused models originate from).

(*OreChem* was adopted by *OPPRA*, *MO* was adopted by *HERACLES*), Earth Science (e.g., *SWEET* ontologies were adopted by *HERACLES*) and Digital Media (*CSO* was adopted by *CHAP*). Furthermore, thesauri, glossaries and controlled vocabularies, specialized either in CnR or in other related domains, were similarly employed

4.3. Deployment

All the models included in the current survey have been employed for developing SW-enabled systems that offer various domain-specific services. In the

course of the survey we identified a number of services that are common among those systems. In particular:

- *semantic search*, which refers to retrieval of CnR data based on the meaning of the search query.
- *data integration* of conservation-related data, derived from remote and possibly heterogeneous sources, into a unified form.
- *visualization* of CnR data (e.g., 2D or 3D visualization of alterations, mind maps).
- *semantic annotation* of i) text with conservation-related content (e.g., scientific papers) or ii) 2D/3D models of conservation objects with sem-

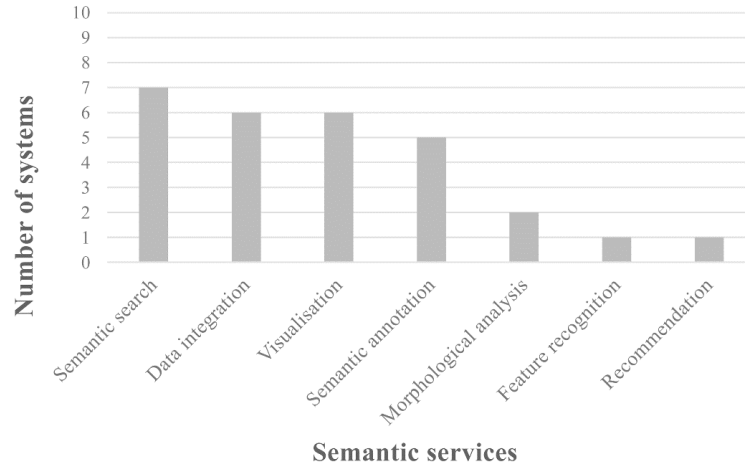


Fig. 3. Provision of services by systems built upon the reviewed models.

antically structured machine-processable data.

- *morphological analysis* of features (related to production and conservation state) of conservation objects (e.g., areas of loss). *feature recognition* (e.g., decorative element, structural element) of conservation objects.
- *recommendation* of digitization and analysis methods based on i) object characteristics and ii) CnR expert's requirements.

Figure 3 depicts the degree to which the identified services are provided by the systems built upon the reviewed models (each model has been deployed in a single system). Apparently, *semantic search* and *data integration* are the most popular among the services provided, while *visualization* follows. The popularity of these services is expected considering that they intend to support CnR decision-making. Decision-making plays a central role in the *day-to-day* work of the CnR professional [34, 46]. In broad terms, decision making in CnR can be thought of as equivalent to the *conservation process* itself [46], since it leads directly to specific intervention actions. Conservators participate in decision-making processes by i) contributing their expertise to a broader, multidisciplinary group of CH experts, and ii) making their own CnR decisions [34]. In this context, *data integration* and *semantic search* provide unified access to the required knowledge/information (in order to make an effective intervention *recommendation*), in this way reducing information retrieval time and improving quality of search results (e.g., information completeness), consequently supporting the overall decision-making pro-

cess. Similarly, *visualization* contributes to CnR decision-making by providing a more articulate and meaningful documentation as well as correlation of the requested information (e.g., the visualization of extent and severity of an alteration phenomenon gives a thorough view of the conservation object's condition). On the other hand, *actual* recommendation of digitization and analysis methods (as an explicit service), is proposed by only one system (the COSCH^{KR} platform). And even in that case, the recommendation merely covers a certain step of the CnR decision-making process, that is selecting the appropriate digitization and analysis method for identifying the technology and condition of a conservation object in order to determine intervention requirements.

4.4. Further Research: Towards an ontology of CnR decision-making

As discussed in the previous section, decision-making constitutes the backbone of the CnR task. Through decision-making the expert transforms various chunks of possibly diverse information relevant to a conservation object, such as scientific information (e.g., material ageing), administrative (e.g., loaning preconditions) or even cultural information (e.g., historical value), into concrete and specific *intervention decisions*. The current survey showed that all the reviewed models more or less represent knowledge relevant to intervention decision-making, and that they have actually been employed for implementing semantic services that support intervention decision-making; alt-

though merely in an *assistive* way (for instance, by offering semantic retrieval of data related to a conservation diagnosis). In other words, the decision-making process *per se*, i.e. including all the parameters, criteria, intervention options etc. potentially involved, and more importantly their complex *interdependence*, which often generates restrictions that can dramatically affect the decision-making outcome, has *not* been modelled as of yet. For example, the *MDO*, *OP-PRA*, *CRMcr*, *CPM* and *HERACLES* models provide the relations necessary to correlate an intervention with i) a conservation object and ii) one or more alteration phenomena. However, as [27] highlight, a simple correlation between conservation interventions and alteration phenomena does not adequately represent the potential complexity of interplay between the various parameters that need to be taken into account in order to come to a valid intervention recommendation.

Drawing on the above, it is strongly suggested that further research should be conducted in order to analyze and conceptualize intervention decision-making at a granularity that will allow a more thorough representation, suitable to drive the implementation of services that will deliver intervention recommendations, as an explicit *decision-support* service. For example, a semantic model of intervention decision-making knowledge by means of a formal ontology can serve as the basis for the development of decision-support systems, with the objective of recommending specific, case-based intervention options. Eventually, such systems will actively assist the CnR expert i) to better organize their thoughts and determine requirements over a decision-making task, and most importantly ii) to retrieve and assess valid intervention options more quickly and effectively. Furthermore, a formal ontology will enable experts to share decision-making knowledge with the wider community in a unified way [9]. Dissemination and exchange of know-how about intervention decision-making among CnR experts is bound to benefit them in multiple ways, for example, in training new professionals or effectively communicating information with clients, stakeholders or other (often interdisciplinary) professional groups [52-53], thus, elevating their work to the next level.

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