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Long-term Sustainable Knowledge Classification with Scientific Computing: The Multi-disciplinary View on Natural Sciences and Humanities

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***Abstract*—This paper presents the methodological and technical results of creating long-term sustainable knowledge resources, which can be used for documentation, classification, and structuring as well as with scientific discovery and deployment of supercomputing resources for advanced information systems. The focus is on the multi-disciplinary knowledge view on disciplines from natural sciences and humanities. The basic requirements resulting from the long-years' cases studies are long-term knowledge resources providing structure and universal classification features. The paper discusses the state-of-the-art implementation of information structures and object representations used with universal classification and computation algorithms for multi-disciplinary, dynamical knowledge discovery. The combination of universal knowledge resources and computational workflows based on High End Computing (HEC) resources and Universal Decimal Classification (UDC) have been successfully used for the goal of creating efficient long-term sustainable Integrated Information and Computing System components. The paper presents practical implementation examples from a range of disciplines with references to natural sciences and humanities, e.g., geosciences, astrophysics, and archaeology. The long-term results show that the overall sustainability principally depends on the methodological and systematical creation of content, structure, and classification with the knowledge resources.**

Keywords*–*Scientific Computing; Sustainability; Knowledge Resources; Multi-disciplinarity; Integrated Systems; Information Systems; Classification; UDC; Natural Sciences; Humanities.

I. Introduction

This paper presents the results and development of applications from long-term sustainable knowledge classification focussing on the multi-disciplinary aspects of natural sciences and humanities. The work and implementation are based on the creation of sustainable knowledge resources supporting structure, classification, and scientific supercomputing for any object and discipline [1]. Systematical and methodological developments are the major sources of contributions for long-term sustainable infrastructures. Technical developments complement the sustainability efforts, contributing to short- and medium-term success. With this context the amount of data as well as the complexity of information keeps steadily increasing. The developments of the last decades have shown that for a continuous positive progress not only the efficiency must increase, the more, developments must be made long-term sustainable, too. As the knowledge gathered during generations should be considered the most important component to the overall success we need universal knowledge resources that can handle documentation as well as universal classification and structuring. As being consent with most contributing disciplines and claimed by scientific councils, the knowledge resources should not only be traditional collections as with digital libraries [2] and isolated content [3] but, despite any challenges be accessible with scientific supercomputing resources in order to create advanced information systems and implement and improve workflows and recommended operation [4], [5].

The created features of the knowledge resources presented for the first time in this paper contain new practical concepts for information structures and object representations. The objects and derivatives, described in this paper, can be used with universal classification and computation algorithms for multi-disciplinary, dynamical knowledge discovery. This paper presents examples from archaeology and geosciences disciplines, resulting from practical case studies on structure and workflow modularisation, within the GEXI collaborations [6]. These are part of a multi-disciplinary knowledge structure. Further, the implementation of the knowledge objects is suitable to be used very flexibly with workflows on HEC resources, e.g., with IICS components [7], [8]. Multi-disciplinary knowledge resources are used to resemble and document of any information available. The requirements for complexity can become arbitrary high so that performant compute resources have to be used for any more advanced applications. The applicability for parallelisation of the contributing algorithms with the complex knowledge trees has therefore been analysed with the case studies. The motivation for investigating in the efficiency and modularisation of the knowledge trees is the increased potential for drastical improvements of the Quality of Data (QoD) with the result matrix, which contributes to advanced cognition within the multi-disciplinary context.

This paper is organised as follows. Sections II and III introduce with sustainability and vitality of knowledge-based architectures and main issues of complexity. Sections IV and V discuss the complexity and present a practically used classification approach to the challenges. Sections VI and VII describe the structure and challenges. Sections VIII and IX introduce the new concept of object carousels, the discovery of "missing links", workflows, references chains, and computational demands. Sections X and XI discuss the lessons learned and summarise conclusions and future work.

II. Previous work

Knowledge creation and knowledge management [9], [10] have been studied for more than twenty years now. Anyhow, so far long-term and sustainability issues have not really been considered in practice, especially in universal multi-disciplinary knowledge context. For example, there have been numberless approaches on knowledge management considering small isolated ranges of classical disciplines or defined purposes but not with multi-disciplinary approaches. Knowledge management (UDC:005.94 Knowledge management) is obvious to be only one of the many aspects of knowledge (UDC:0 Science and knowledge), from creation to organisation and universal and long-term sustainable development and use [11].

For all components presented in this paper, the main information, data, and algorithms are provided by the LX Foundation Scientific Resources [12], e.g., the volcanological data, the meteorite crater data, and archaeological data.

Information about the following data sources has been integrated and deployed with the knowledge resources for the previous basic case studies and developments. So, the creation of long-term knowledge resources decisively contributes to the goal of a successful creation of long-term sustainable Integrated Information and Computing System (IICS) components.

The referred "Leibniz" data (see the following references on Gottfried Wilhelm Leibniz, 1646–1716) has been included into the workflow chains, e.g., creating historical associations with the the content of archaeology and geosciences will otherwise not be accessible. An example is the communication regarding volcanoes, earthquakes, and caves in manuscripts and letters or content of pictorial realia objects, which are not available via search engines. From the Leibniz sources there is a rich contribution for the result matrix on volcanism, volcanology, and geology by various historical objects, references, and sources, especially for volcanism, Vesuvius [13], as well as earthquake related context [14], even from concept glossaries [15], manuscript collections and catalogues [16], [17] as, e.g., [18], [19], or Leibniz related copperplates [20]. For example, the "praehistoric unicorn" reconstruction [21], as well as material on geological context has not been referenced before from knowledge resources' objects and is not freely and publicly available as a direct reference, media or verification [22].

Material in specialised collections, for example in the European Cultural Heritage Online [23] would not be easily accessible due to the type and context of the material.

Further data being publicly available can be incorporated in any way under the premise that the data formats are accessible and interfaces have been provided. An example is the CLImatological database for the World's OCeans (CLIWOC) [24], a climatological database for the world's oceans from 1750–1850, containing digitized data from logbooks of pre 1854 voyages of English, Spanish, Dutch, and French ships.

III. Sustainability and vitality

In the context of this research, the goal for "long-term" means > 50 years. The long-term strategy has been discussed in detail with previous implementations [25]. Data mining is not only an analysis step of knowledge discovery in databases based on informatics but much more general in data pools. It is an inter-disciplinary as well as multi-disciplinary field of many sciences and computer science. It means discovering patterns in data pools using methods implementing statistics, classification, artificial intelligence, learning and many more based on knowledge resources. The process targets to extract information from knowledge resources and gaining content and context, e.g., based on structure and references, in order to prepare for further use. Sustainable long-term strategies have to combine operation, services, and especially the knowledge resources [26], [1]. With the available systems components, we have Resources Oriented Architectures (ROA), Services Oriented Architectures (SOA), and "Knowledge Oriented Architectures" (KOA) in addition [27]. For long-term operation, all three must be obtained from the creation and operation. Considering the entirety of aspects necessary for a successful long-term change management with future information technology structures. Nevertheless, the KOA is the most important complement as it contains the highest percentage of the overall investments for the results and the data that may even not be reproducible later on.

IV. Complex knowledge resources case

Central aspects for uses cases are the definition of knowledge and the features of the knowledge resources.

A. Knowledge definition

In general, we can have an understanding, where knowledge is: Knowledge is created from a subjective combination of different attainments as there are intuition, experience, information, education, decision, power of persuasion and so on, which are selected, compared and balanced against each other, which are transformed and interpreted.

The consequences are: Authentic knowledge therefore does not exist, it always has to be enlived again. Knowledge must not be confused with information or data which can be stored. Knowledge cannot be stored nor can it simply exist, neither in the Internet, nor in computers, databases, programs or books. Therefore, the demands for knowledge resources in support of the knowledge creation process are complex and multifold.

There is no universal definition of the term "knowledge", but UDC provides a good overview of the possible facets. For this research the classification references of UDC:0 (Science and knowledge) define the view on universal knowledge.

B. Knowledge resources

The knowledge resources created can integrate any object. These objects can be described with universal classification, handled with phonetic algorithms [28], [29], and can refer to external resources. The structure of the knowledge objects has to support the modularisation for application scenarios where the workflow has to allow highly efficient implementations itself. Creating workflows based on the multi-disciplinary knowledge matrices therefore requires highly performant resources. The overall big data challenges, data intensive volume, variability, velocity and for future scenarios especially data vitality, meaning long-term documentation, usability, and accessibility can be handled in a scalable, modular way. Further, the components created are considered to become objects of sustainable knowledge resources, for long-term persistent big data vitality of documentation, processing, analysis, and evaluation. The created solution for long-term use meets a number of attributes, e.g., it should be generic, superior, adaptable, flexible, seminal sustainable. In summary, these combined vital features are called “eonic”.

V. Knowledge resources classification support

The operated knowledge resources, based on the LX Foundation Scientific Resources [28], incorporate UDC classification support for any discipline and purpose, e.g., for knowledge discovery and workflows. Practical summarising excerpt subsets for specific disciplines used with the case studies presented here are given in Tables I, II, III, and IV. These subsets are use with the knowledge resources on classification regarding archaeology, volcanoes, impact events, and sinkholes.

Table I. Archaeology knowledge resources classification.

UDC Code	*Description*
UDC:902	Archaeology
UDC:903	Prehistory. Prehistoric remains, artefacts, antiquities
UDC:904	Cultural remains of historical times
UDC:930.85	History of civilization. Cultural history
UDC:”63”	Archaeological, prehistoric, protohistoric periods, ages
UDC:(23)	Above sea level. Surface relief. Above ground generally.
UDC:(24)	Below sea level. Underground. Subterranean
UDC:=14	Greek (Hellenic)
UDC:56	Palaeontology
UDC:55	Earth Sciences. Geological sciences
UDC:711.42	Kinds of town, locality, settlement
UDC:720.2	Architecture techniques and methods
UDC:720.31	Prehistoric architecture
UDC:720.32	Ancient architecture

Table II. Volcanoes knowledge resources classification.

UDC Code	*Description*
UDC:532	Fluid mechanics in general.
UDC:550.8	Applied geology and geophysics. . . .
UDC:550.93	Geochronology. Geological dating. . . .
UDC:551	General geology. Meteorology.
UDC:551.1	General structure of the Earth
UDC:551.2	Internal geodynamics (endogenous processes)
UDC:551.21	Vulcanicity. Vulcanism. Volcanoes. Eruptive phenomena.
UDC:551.23	Fumaroles. Solfataras. Geysers. Hot springs. Mofettes.
UDC:551.24	Geotectonics
UDC:551.26	Structural-formative zones and geological formations
UDC:551.4	Geomorphology. Study of the Earth’s physical forms
UDC:551.44	Speleology. Caves. Fissures. Underground waters
UDC:551.462	Submarine topography. Sea-floor features
UDC:551.5	Meteorology
UDC:551.588	Influence of environment on climate
UDC:551.7	Historical geology. Stratigraphy
UDC:551.8	Palaeogeography
UDC:552.2	General petrography. Classification of rocks
UDC:552.6	Meteorites
UDC:631	Agriculture in general
UDC:631.4	Soil science. Pedology. Soil research

Tables III and IV show the excerpts used for basic impact events and sinkholes classification.

Table III. Impact events knowledge resources classification.

UDC Code	*Description*
UDC:5	Mathematics and natural sciences
UDC:500	Natural sciences
UDC:539	Physical nature of matter
UDC:539.63	Impact effects
UDC:539.8	Other physico-mechanical effects

Table IV. Sinkholes knowledge resources classification.

UDC Code	*Description*
UDC:519.2	Probability. Mathematical Statistics
UDC:556.34	Groundwater flow. Well hydraulics
UDC:624	Civil and structural engineering
UDC:624.151	Foundations. Foundation bed
UDC:699	Protection of and in buildings. Emergency measures
UDC:930.85	History of civilization. Cultural history
UDC:528.9	Cartography. Mapping (textual documents)
UDC:726.6	Cathedrals. Basilicas. Domes

The small unsorted excerpts of the knowledge resources objects only refer to main UDC-based classes, which for this part of the publication are taken from the Multilingual Universal Decimal Classification Summary (UDCC Publication No. 088) [30] released by the UDC Consortium under the Creative Commons Attribution Share Alike 3.0 license [31] (first release 2009, subsequent update 2012).

As one of the elementary qualities, the LX Foundation Knowledge Resources allow to refer to any kind of references, therefore they also allow to refer to any kind of classification. If nothing special is mentioned then all the basic classification codes are used in an unaltered way. If any classification refers to a modified code then the authors of contributions have to notice and document the modifications explicitely. The classification sets have been referred to and used with the presented computation. UDC [32] currently provides around 70,000 entries in about 100 top classes, whereas the UDC Summary [33] provides a selection of more than 2,000 classes. The multi-lingual support lists translations in about fifty languages [34], [35]. UDC classifications have been integrated with tens of thousands of knowledge objects [29], which are a base for each computation [34], [36], [11].

VI. Structure related support

For the components shown here, the structuring capabilities of the the LX Foundation Scientific Resources [12] have been deployed. Mostly any external information and types of objects can be integrated into this structure. The figures, object entries, and photo media samples shown in the passages of the following case study examples are computed from the content of the LX Foundation Scientific Resources. Figures, object entries, and photo media samples © C.-P. Rückemann, 2011, 2012, 2013, 2014).

Structuring information requires a hierarchical, multi-lingual and already widely established classification implementing faceted analysis with enumerative scheme features, allowing to build new classes by using relations and grouping. This is synonym to the Universal Decimal Classification (UDC) [37]. In multi-disciplinary object context a faceted classification does provide advantages over enumerative concepts. Composition/decomposition and search strategies do benefit from faceted analysis. It is comprehensive, and flexible extendable. A classification like UDC is necessarily complex but it has proved to be the only means being able to cope with classifying and referring to any kind of object.

Copies of referred objects can be conserved and it enables searchable relations, e.g., for comparable items regarding special object item tags. The UDC enables to use references like for object sources, may these be metadata, media, BibTeX sources or Digital Object Identifier (DOI) [38] as well as for static sources. With interactive and dynamical use for interdisciplinary research the referenced objects must be made practically available in an generally accessible, reliable, and persistant way. A DOI-like service with appropriate infrastructure for real life object services, certification, policies and standards in Quality of Service, for reliable long-term availability object, persistency policies should be available.

Therefore, for any complex application, these services must be free of costs for application users It would not be sufficient to build knowledge machines based only on time-limited contracts with participating institutions. These requirements include the infrastructure and operation so data availability for this long-term purpose must not be depending on support from data centers providing the physical data as a "single point of storage". Unstructured information, the data variety, is one major complexity. For relational databases, a lot of players providing offerings in this space go through the cycle of what the needs are for structured data. As one can imagine, a lot of that work is also starting for unstructured or semi-structured data with Integrated Systems. Data access and transfer for structured data, unstructured data, and semi structured data may be different and may to a certain extend need different solutions for being effective and economic [39].

The long-term objects must be able to contain the essential knowledge, even as medium- and short-term objects cannot be preserved or made persistent as, e.g., DOI (Digital Object Identifier), URN (Uniform Resource Name), URL (Uniform Resource Locator), and PURL (Persistent Uniform Resource Locator) will vanish and context and sources may fade away as well as OS (Operating System) features used. Therefore, we have to distinct between the real instance of a DOI and URL or a context situation and a descriptive reference of these objects. These descriptive references can contain as much information and knowledge as possible (for example DOI, URL, context description, sources).

VII. Coping with the Challenges

A. *Modular components for geoscientific applications*

Complex geophysical exploration is an explicit big data problem. Data locality and data movements are of essential importance. Therefore, data handling does take longer a time than the compute intervals. Due to the short intervals for licensing and the high costs even the time efficiency has to be increased. This can be supported by parallel techniques [40], [41], [42]. In many multi-disciplinary cases, e.g., explicitely shown with the case studies [7], [28], the more with growing importance of evaluation processes, the task- and thread-parallelity has to be increased both. The data in geosciences and in associated natural sciences contains the most valuable information because many of these natural processes change in geological time intervals. Imaging for oil and gas is one of the most demanding tasks in computational sciences. It requires scale-out architectures, the processing and simulation are computation intensive as well as data intensive. The data provides long-term challenges on knowledge and resources to researchers and industry because of expenses on data collection and long-term usability.

B. *Rising requirements on quantity and computation*

As soon as even a selected subset of the available classification is integrated with a subset of detailed knowledge resources, the requirements for computing and interfaces are rising drastically. The increasing demands for advanced scientific computing are resulting from the huge number of relations within the knowledge resources as well as a consequence of the workflows, dynamical interaction, presentation, and visualisation of results. The conditions for the optimal computing architecture are defined by the application scenario, not by the knowledge resources themselves.

C. *Quality for Quantity*

For the discovery of a result matrix from a large quantity of data, additional high quality resources can be used for improving the quality of results deduced. The premise is that appropriate workflows and algorithms will be applied. The high quality knowledge resources have been used as "Quality for Quantity" (Q4Q), in order to build any additional missing references in the quantity data. With these HEC and discovery processes, big data means volume regarding storage, means variability regarding workflow processes, means velocity regarding instances, and vitality regarding knowledge resources.

VIII. Object Carousels

The organisation of the knowledge objects can be arbitrary complex. Many cases can be described in a simplified way like a mindmap, which has been used for introducing a new symbolic representation named "object carousels". The knowledge objects build a kind of dynamical molecules. These molecules have connectors and references. These connectors can connect with other knowledge objects by computing references from any number of directions. The process reminds of rotating branches of trees, rings, and multi-dimensional objects for finding pluggable connections. The creation of object carousels does have the benefit, that knowledge discovery workflows can be implemented very scalable, using various algorithms for connecting trees. For example, full text references can be used between any carousels in order to compute a result matrix.

A. Object mapping

The mapping in Figure 1 shows an excerpt for the volcanology context on terrestrial volcanism calculated from the knowledge resources. These allow to calculate relations via flexible, user-defined algorithms.

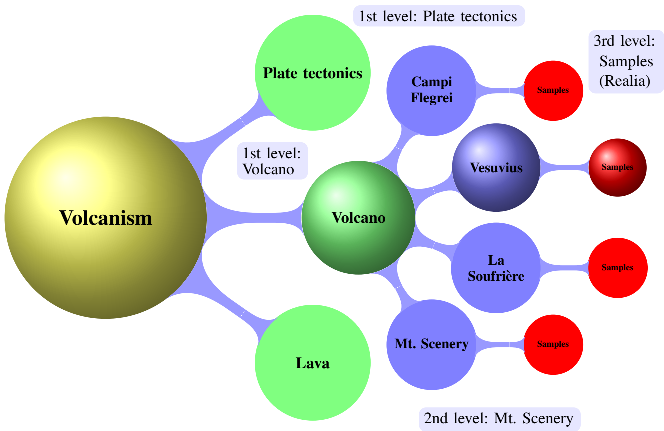

Figure 1. Object carousel for terrestrial "volcanism" context with subset of computed volcano references and examples of levels object relations.

The figure shows an excerpt of the direct relations by quality of relations and quality of objects. The colours visualise object groups or attributes within each figure. Any object or attribute can dock-in at any placed defined by the workflows, not depending on the grouping. Nevertheless, the decision within the workflow maybe assisted by the group information. The knowledge resources can contain objects and relations as well as classification entries. The case study example being the base for illustrating the different aspects in all the next sections follows a discovery path (3D), starting discovery on object and realia references in the volcanology dimension.

B. Information and object usage

In a non-promoted environment, a knowledge search engine showed significant requirements with up to over 500,000 application- and several million object-requests per day. The study on object usage from international public interest groups done in a time interval from 1994 to 2012 [6] revealed comparable large numbers of accesses and complexity. The object mapping is a basic part, whereas the algorithmic workflow for improving the quality can be as expendable as using every information available with each step recursively and iteratively. The computation share can increase to hours per discovery instance but computation can be done for any number of carousels in parallel. The KOA opens flexible support for task and process parallelity for using objects and object groups or clusters.

C. Case study views

Suitable views for volcanoes are: Type (of volcano, coarse categories), date on timeline, size (height). For craters respective views are: Type (of crater, fragmentary), date on timeline, size (diameter). An object carousel generated for volcano types, shows the knowledge resources groups (Figure 2).

Figure 2. Object carousel for volcano and type references computed for terrestrial volcanism, providing volcano type references.

An object carousel generated for impact craters, shows the different types present in the knowledge resources groups and their crater categories (Figure 3).

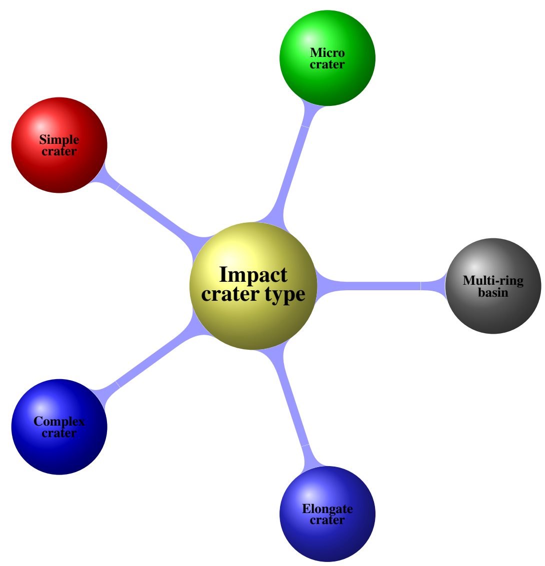

Figure 3. Object carousel computed for impact crater categories.

Criteria for impact crater classification are:

- Size of the impacting object,
- Speed of the impacting object,
- Material of the impacting object,

- Composition and structure of the target rock,
- Angle that the impacting object hits the target,
- Gravity of the target object respective planet,
- Porosity and other attributes of the impacting object,
- Age of the impact,
- Size of the impact,
- Structure of the crater.

Impact crater indicators, for example:

- Planar fractures in quartz,
- Shocked quartz,
- Glass fragments.

If approaching from the "catastrophe" view it has shown that the most prominent relation is the "size". This mostly correlates with "diameter" and still mapping and timelining will come natural.

A comparable object carousel for impact crater types and geological period references is provided in Figure 4.

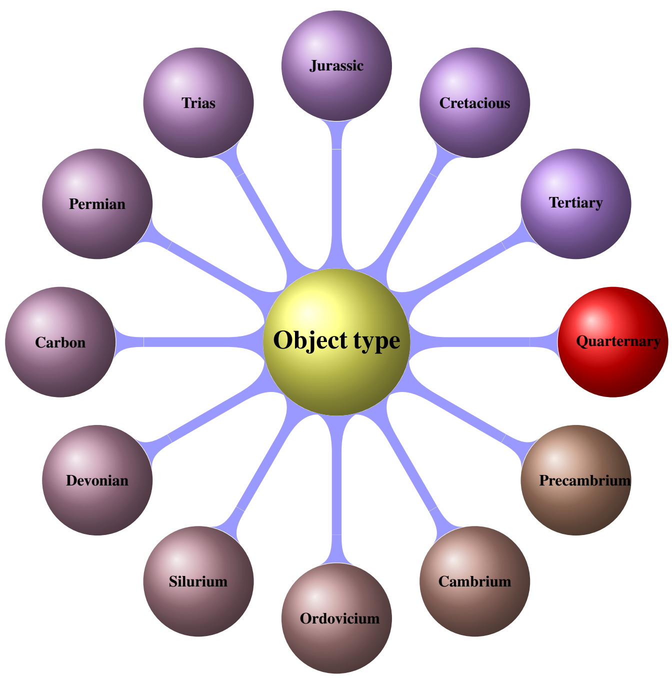

Figure 4. Object carousel object type for computed period references (terrestrial volcanoes, impact craters, and geological processes).

An evaluation of the association that users have, showed that the criteria "date" and "location" are most prominent with objects if the workflow approaches from the "surface (of the earth)" view. Therefore, mapping and timelining will be the natural result.

D. Improving quality within the workflow

The resources, workflow, and classification are essential for a high level of usability quality of results. The elaborate workflow process for improving the quality of results when calculating a result matrix from a knowledge base is:

a) Calculate associator attributes and classes,
b) Compute on a base with large numbers of objects,
c) Evaluate detailed classification information,
d) Compute for a reduction of numbers of objects,
e) Create suggestions and recommendations.

The first computation block (b) is needed for considering more objects when applying the further steps afterwards. Here, the classification is essential for improving the quality for the respective selection process. The second computation block (d) is necessary for improving a selection process for the target audience or services. The selection processes can be significantly supported by high quality knowledge resources (Q4Q), e.g., via the authored, classified, and audited content, with regular expression search, and phonetical algorithms.

E. Improving coverage: Dark data

In analogy to "dark matter" and "dark energy", there exists "dark information" and to an uncertain extent an unknown driving force in knowledge creation, even building "dark service" provided via "dark resources". Those information resources are not wider accessible and it is not known where the intention of gathering and creation. Anyway, this information must be considered for any holistic long-term concept as it provides an important factor for the overall knowledge and will stay in existance despite of any development. With the concept of long-term knowledge resources the information has been integrated in order to extend the base for any knowledge discovery. Considered methods for integration of resources are, e.g., references, description or caches. This further includes seamless updating of information, licensing of resources, dynamical use of data as well as provisioning of defined quality and reliability for sources and complements.

IX. Discovery of Missing Links

From the disciplines of humanities and archaeology, the directed tree spanning from settlements to used materials will show up with a practically defined depth. On the other hand, starting from natural sciences a directed tree spanning to materials associated with processes will deliver a natural sciences path. Along with the different paths, the genetic connectors of both carousels will show up with links from both directions. The connecting links, or short "connections" from the directed search do open new associations that can be used to discover the overall knowledge much deeper with new facets and quality, which provide multi-disciplinary links that have been missing in non-genetic discovery.

In general, any kind of tree path can be generated from the knowledge resources using a workflow and any number of carousels can be discovered for connections. The following example shows a simple two-carousel case (Figure 5). Computing the object carousels connections is shown for a historical city carousel and an environment object carousel. The trees show a subset of computed references computed by the workflow within the knowledge resources. The depth of the trees may by different for the computation. The connections are considered as soon as they lead to a defined conformity. In that case, defined conformity can mean comparable or identical. The example shows two trees, one from archaeology and one from natural sciences disciplines. For both, at a certain branch leading to object referring to stone material, which is shown by the highlighted red bullets.

A. Computing connections on modular objects

Figure 5 shows the principle used for computing connections with object carousels. It depicts one fitting branch, within archaeology and geosciences associated objects. Starting with the objects `Historical City` and `Environment` (identified by large golden bullets) and the linking objects "stone" the computed carousels show trees with a subset of references. The workflow attributes have been choosen to provide no tree depth restriction for computation. The two fitting connection lines within the object carousels of this example are highlighted in a three-dimensional representation: `Roman : Pompeji : Napoli : Architecture : Volcanic stone` and `Volcanology : Catastrophe : : Volcanic stone`. In the sample workflow, the carousel connections are calculated via non-explicit references of comparable objects (red objects) from knowledge resources within trees. In addition, the red circle does mark those objects at the same depth level, including the fitting object term for historical city and environment `Volcanic stone`. The excerpt of associated multi-disciplinary branch level objects are `Limestone`, `Impact feature`, and `Climate change`.The method for creation of non-explicit references can be defined in the workflow. Here, full text mining and evaluation (red objects) has been used. For derivated associations additional objects can be computed and extracted in every branch as well as on all levels.

B. Connecting knowledge

Objects can be connected by various attributes. These may be attributes associated with content as well as with context. For example, relations for a volcano object can be connected and triggered by a large variety of attributes. Table V shows an excerpt of attributes and examples.

Table V. ATTRIBUTES LINKING AND TRIGGERING VOLCANO OBJECTS AND SELECTED EXAMPLES (EXCERPT).

Attribute	*Example in Archaeology/Geosciences*
`Time`	Events on timeline
`Location`	Volcano-impact-settlement locations
`Physics`	Earthquakes
`Chemistry`	Volcanic SO_2 ejection
`Geology`	Earth crust, petrography
`Catastrophes`	Volcanic eruptions, Tsunamis
`Etymology`	Phlegra, Vesuvius
`Cults, religions`	Volcano gods
`Artefacts`	Archaeological objects, "Pompeji" events
`Historic events`	Volcano, climate, economy, revolution

Relations can refer to any multi-disciplinary topic, building results from combination of information and generation of new objects and references, e.g., visualisations and views.

Selecting "catastrophe" categorised objects from the knowledge resources results in a matrix including groups of keywords, for example:

1) `Meteorite, impact, Yucatan, Mexico, dinosaurs, extinct, Cretaceous, CT boundary, catastrophe.`
2) `Volcano, eruption, Santorini, Thera, crete, Minoan civilisation, culture, Mycenae, culture, fleet, volcanic ash, vanish, rise, historical city, catastrophe.`
3) `Volcano, Vesuvius, Campi Flegrei, phlegra, scene of fire, Pompeji, Herculaneum, volcanic ash, lapilli, catastrophe.`
4) `Solfatara, volcano, Vesuvius, Campi Flegrei, phlegra, scene of fire, Pompeji, Herculaneum, volcanic ash, lapilli, catastrophe.`

For example, following an etymological tree leads from 'Vesuvius — Campi Flegrei' to "phlegra" greek for 'scene of fire'. The above keyword groups resolve to object entries, for example

1) `Chicxulub,`
2) `Thera, Santorini,`
3) `Vesuvius, Pompeji,`
4) `Solfatara.`

. These objects refer to media samples as shown with some examples for Vesuvius, Pompeji, and Solfatara.

The following excerpt contains some structure, UDC classification, keywords, references, and satellite image reference. The references for the geopositioning are created via classification and can be used for any purpose. Listing 1 shows an excerpt of an LX Resources object entry [43], "Vesuvius" volcano.

```
Vesuvius [Volcanology, Geology, Archaeology]:
         (lat.) Mons Vesuvius.
         (ital.) Vesuvio.
         (deutsch.) Vesuv.
         Volcano, Gulf of Naples, Italy.
         Complex volcano (compound volcano).
         Stratovolcano, large cone (Gran Cono).
         Volcano Type: Somma volcano,
         VNUM: 0101-02=,
         Summit Elevation: 1281\UD{m}.
         The volcanic activity in the region is observed
          by the Oservatorio
         Vesuviano. The Vesuvius area has been declared a
           national park on
         \isodate{1995}{06}{05}. The most known antique
          settlements at the
         Vesuvius are Pompeji and Herculaneum.
         Syn.: Vesaevus, Vesevus, Vesbius, Vesvius
         s. volcano, super volcano, compound volcano
         s. also Pompeji, Herculaneum, seismology
         compare La Soufrière, Mt. Scenery, Soufriere
         %%IML: UDC
          :[911.2+55]:[57+930.85]:[902]"63"(4+23+24)
          =12=14
         %%IML: GoogleMapsLocation: http://maps.google.de
          /maps?hl=de&gl=de&vpsrc=0&ie=UTF8&ll
          =40.821961,14.428868&spn=0.018804,0.028238&t=h&
          z=15
```

Listing 1. Knowledge resources – object entry "Vesuvius" volcano.

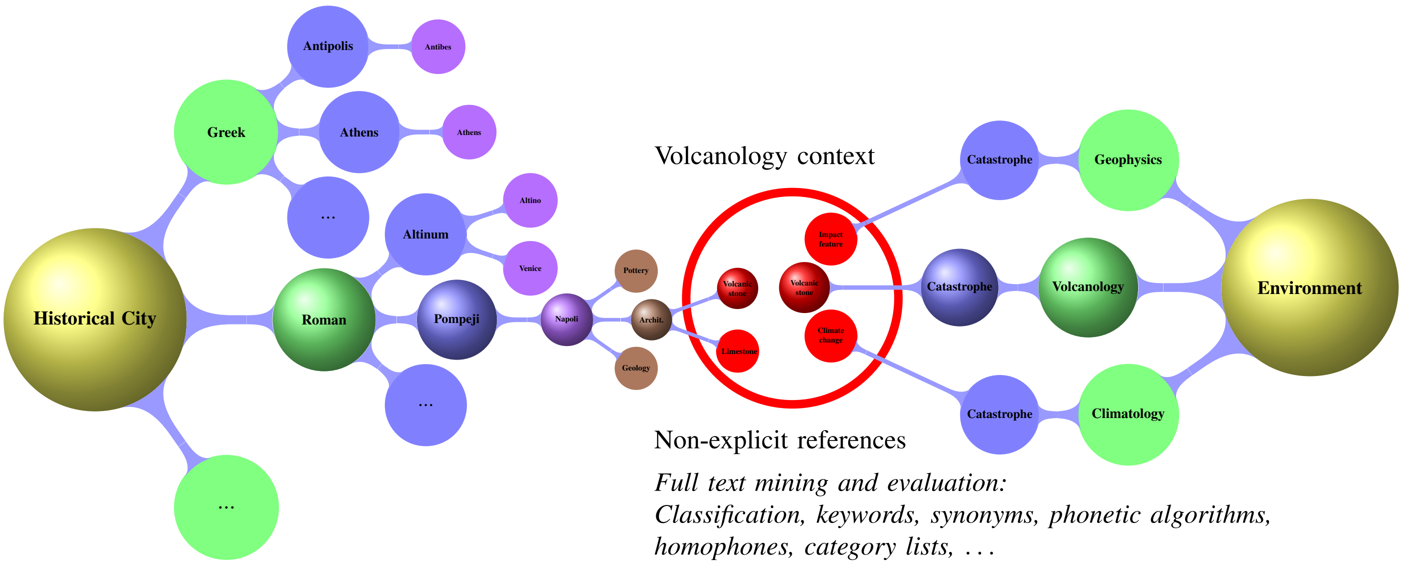

Figure 5. Computing object carousel connections: Historical city and environment object carousels showing trees with a subset of computed references. In this sample workflow the carousel links are calculated via non-explicit references of comparable objects (red) from knowledge resources within trees.

The example contains a reference and VNUM for the Vesuvius volcano, various secondary objects, UDC classification, satellite image reference and, e.g., refers to “Soufriere”, “La Soufrière”, and “Mt. Scenery”.

Listing 2 lists an entry excerpt for realia material associated with the Vesuvius volcano.

```
Object:              Volcanic material.
Object-Type:         Realia object.
Object-Location:     Vesuvius, Italy.
Object-FindDate:     2013-10-00
Object-Discoverer:   Birgit Gersbeck-Schierholz, Hannover,
   Germany.
Object-Photo:        Claus-Peter Rückemann, Minden,
  Germany.
Object-Relocation:   Claus-Peter Rückemann, Minden,
  Germany.
%%IML: media: ... img_2402.jpg
%%IML: media: ... img_3823.jpg
%%IML: media: ... img_3824.jpg
%%IML: UDC-Object:[551.21+55]:[911.2](37+4+23)=12
%%IML: UDC-Relocation:069.51+(430)+(23)
%%IML: cite: YES 20130000 {LXK:High End Computing;
  Knowledge resources; Objects; Archaeology; Geosciences;
  Vesuvius; Pompeji} {UDC:...} {PAGE:----.----} LXCITE://
  Rueckemann:2013:Computing_Objects
%%IML: cite: YES 20140000 {LXK:Nature; History; Napoli;
  Vesuvius; Pompeji} {UDC:...} {PAGE:----.----} LXCITE://
  Gersbeck:2014:Vesuvius
```

Listing 2. Knowledge resources – Entries for Vesuvius material.

Besides the UDC object and relocation data the excerpt carries the media references and citations and originating sources, researchers, and relocation for the realia objects.

Figure 6 illustrates the computed objects (Topicview), here the latest available volcanic samples for Vesuvius, after processing showing the variety of material from the Vesuvius volcano.

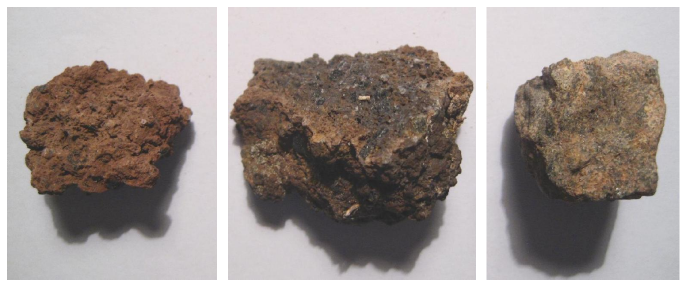

Figure 6. Topicview result matrix – Vesuvius realia objects (excerpt): Range of volcanic ashes and lapilli (Vesuvius, 2013).

Any of these objects being part of the resulting matrix for a request, e.g., photos for object entries as well as media data for physically available samples, have been found via references and UDC from the knowledge base (`UDC:551.21...`). The realia references for the objects refer to a collection where the samples are stored. Further analysis for the samples is available via the knowledge resources.

Figure 7 illustrates the computed objects (Topicview) of realia objects associated with “Vesuvius”.

Figure 7. Topicview result matrix – “Vesuvius” associated realia objects (excerpt, from left to right): Solfatara sample (2013), Pompeji lapilli (2013), Pompeji plaster sample (2013).

The selection criteria are "archaeology, artefacts, cultural remains of historical times, architecture techniques and methods, ancient architecture" (`UDC:902`, `UDC:903.2`, `UDC:904`, `UDC:720.2`, `UDC:720.32`). The associated views show a sample from the Solfatara (sample front side and sample rear side) near Vesuvius and a sample of a Pompeji plaster (Pompeji style I, incrustation style).

Figure 8 illustrates a specific selection (Topicview) of "Vesuvius" realia objects.

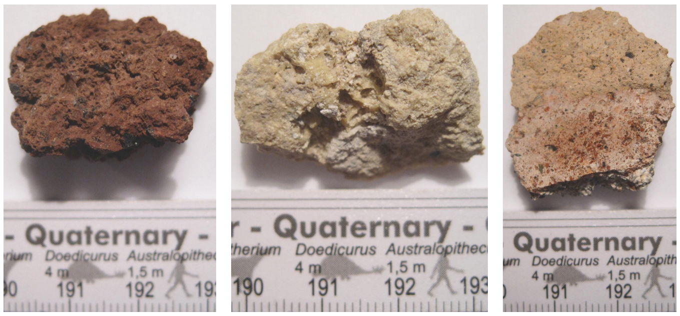

Figure 8. Topicview result matrix – "Vesuvius" and associated realia objects with measure (excerpt, from left to right): Vesuvius lapilli (2013), Solfatara sample (2013), Pompeji plaster sample (2013).

The associated views show a sample from the Solfatara (sample front side and sample rear side) near Vesuvius and a sample of a Pompeji plaster (Pompeji style I, incrustation style). The media samples shown are part of comprehensive classified object entry descriptions and the citations refer to [44]. Respective object entries have been shown and discussed in detail in the context of the component implementations [25].

C. Generation and combination of knowledge

The following visualisations paradigmatically illustrate results from the compute requests based on the content of the implemented content. An on-location attribute has been choosen for the relations in order to compute a distribution map for volcanological features using the `lxlocation` workflow. The location attribute is suitable for referring to an unlimited number of further multi-disciplinary information in this case. A sample distribution of classified terrestrial volcanological features is depicted in Figure 9.

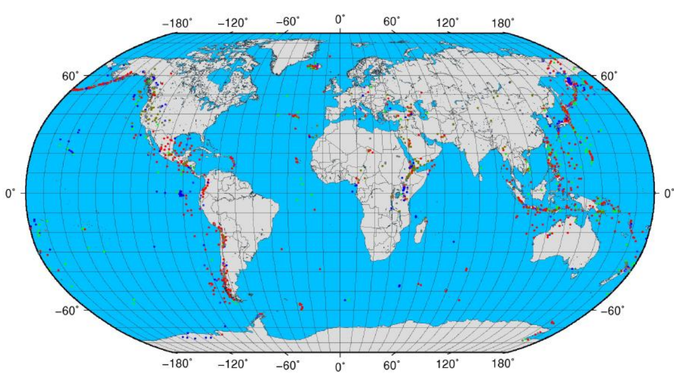

Figure 9. Volcanomap – worldmap for classified volcanological features.

The map is computed from the related object context contained in a volcanological features research database of the knowledge resources. The volcanological features are classified and several classification groups have been choosen for the result. The map shows the present situation according to the available volcanological data. The associated sample distribution of terrestrial impact features (meteorite) is depicted in Figure 10.

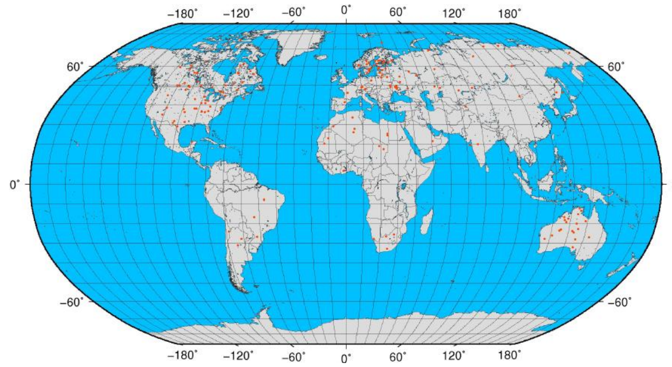

Figure 10. Impactmap – worldmap for impact features (meteorite).

The map is computed from the related object context (`lxlocation` workflow) contained in a meteorite impacts features research database of the knowledge resources.

The visualisations are based on the results gathered in the knowledge resources, several thousands of objects from research and documentation, with several ten thousand attributes and references. It is possible to combine any information, for example, computing a map animation varying in time, showing the development of volcanological or impact features.

D. Case lessons learned

- Impact features have been reduced by morphological processes and are mostly only available above sea-level.
- Volcanic features are well known above and below sea-level and are more often long-term processes.
- Known impact features show a concentration in highly populated and industrialised areas.
- Both impact and volcanological features are related to social and archaeological findings.
- Both impact and volcanological features are publicly known.
- Compared with impacts and volcanological features, archaeological sites and results are not known to the same amount in order to protect the sites.

E. Classification groups

Inserting an additional object classification can extend the range of objects and disciplines. Two small examples from the context of volcanology and meteorites will show the effect on terrestrial to extra-terrestrial result matrices.

Including non-terrestrial volcanism will further lead to special object carousels. The references on "classification" of volcanological features and distribution also explicitely leads to extraterrestrial volcanism [45]. Therefore, volcanological features on Venus from Magellan data provided from this source holds additional objects: Shield fields, intermediate volcanoes, large volcanoes, calderas, coronae, arachnoids, novae, lava floods, lava channels. Besides the above features, the volcanological and magmatic features further create references to: Vents, fields, intermediate volcanoes, steep-sided domes, tadpoles, sinuous channels, lava flows, amoeboids, festoons, and so on.

Comparable, including non-terrestrial meteorites will further lead to special object carousels, e.g., delivering data for craters on Moon and Mars.

F. *Reference chains and historical knowledge*

It is well known that publication references and citations are important. Besides publications, why are secondary and tertiary references on knowledge objects important? Secondary and tertiary references are as well a reliable and stable means of documentation and as well a dynamical means of optimising knowledge discovery workflows.

In this context, secondary references are links and direct references to other objects. Tertiary references are explicit or non explicit references within sets of objects.

These references are stable because they document a certain state within space and time. At the same time these references have dynamical features because their content and context can be used dynamically with workflows as well as they can refer to dynamically handled content and context.

A practical example workflow using the information on Gottfried Wilhelm Leibniz (1646–1716) in different context shows how to integrate certain historical knowledge with the knowledge resources on natural sciences in order to extend the range of discovery. The following is not a simple 'search example' but a successful integration of valuable but weakly structured knowledge data and information into advanced knowledge resources. The results are advanced discovery and research facilities.

Data referring to the "Leibniz archives" [46] has been used for extending the reference chain. The archives are a valuable source of information, which can be used to extend workflows based on knowledge resources in the future. The result matrix for "Saturn" has been computed via the workflow chain including the "Leibniz" objects including link and keyword context for creating intermediate result matrices. This includes references from concept glossaries [15] with transcriptions and scans as well as the LeibnizCentral manuscript collections and catalogues [17].

In this example, the "Saturn Rings", Leibniz, and early discoverers and scientists have up to now not been interlinked by any other available knowledge resource or referenced by any published documentation. The following methodology has been used for creating a result matrix. Links have been created by selecting the maximum time range of Leibniz dates and possible research topics and searching for research topics of other researchers in that time interval.

An algorithm supports UDC classification, building groups of pseudonyms, translations, corrections, and phonetic support based on computed LX Soundex codes for name selection used in context with Leibniz.

The result matrix contains references and associations to topics and researchers at the time of Gottfried Wilhelm Leibniz who were involved or engaged in research on comparable or even different topics. This allows to suggest which topics have been present and Leibniz may have been recognised or even which he might not have known of. Listing 3 shows an excerpt from the keyword context data of a 'Leibniz'-object "Saturn".

```
...
link-Context: LNK :: http://www.uni-muenster.de/Leibniz/
 DatenII2/II2_B.pdf
keyword-Context: KYW :: planetae (Planeten), Venus
...
link-Context: LNK :: http://www.uni-muenster.de/Leibniz/
 DatenII2/II2_B.pdf
keyword-Context: KYW :: planetae (Planeten), Saturn
...
link-Context: LNK :: http://www.uni-muenster.de/Leibniz/
 DatenII3/II3_B.pdf
keyword-Context: KYW :: planetae (Planeten), Saturn
...
link-Context: LNK :: http://www.bbaw.de/bbaw/Forschung/
 Forschungsprojekte/leibniz_potsdam/bilder/IV6text.pdf
link-Context: LNK :: http://www.nlb-hannover.de/Leibniz/
 Leibnizarchiv/Veroeffentlichungen/III7A.pdf
keyword-Context: KYW :: Saturn, Ring
...
```

Listing 3. Keyword context data from 'Leibniz'-object "Saturn" (excerpt).

The references resolve to the secondary data at the TELOTA service [47], using the terms "Saturn" [48] and "Planet" [49]. The links to the references are provided by different institution or respective domains [50], [51], [52]. The `II3_B` link fails as this information is not available, which is true for more than 20 other links, too, referring to this resource from this request. Even the other references from this service require additional support as they differ essentially regarding their bibliographic data, which is missing in some cases, as well as their scheme is not consistent.

Anyhow, with the correction, classification, and context support of the knowledge resources an interesting example, which has been resolved from the LX Foundation Scientific Resources is the discovery of the separation of the rings of the planet Saturn, for which sources exist documenting that the separation has been detected and recognised by Guiseppe Campani in the year 1664, about ten years before it has been published by Giovanni Domenico Cassini.

Listing 4 shows an excerpt of a secondary citation reference set used with UDC classified knowledge objects.

```
Saturn              [Astronomie, ...]:
                    Sixth planet from the sun, a gas
                     giant or Jovian planet.
                    Saturns'␣most␣prominent␣feature␣is␣
                     the␣Saturn␣ring␣system.
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Guiseppe␣Campani␣detected␣and␣
 recognised␣the␣separation␣of␣the␣Saturn␣rings␣in␣the␣
 year␣\isodate{1664}{}{}.
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣%%IML:␣cite:␣NO␣␣16640000␣{
 LXK:Saturn;␣Saturn␣ring␣system;␣solar␣system;␣planets;␣
 discovery}␣{UDC:...}␣{PAGE:----..----}␣LXCITE://
 Campani:1664:Saturn
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣%%IML:␣cite:␣NO␣␣20070000␣{
 LXK:Saturn;␣Saturn␣ring␣system;␣solar␣system;␣planets;␣
 discovery}␣{UDC:...}␣{PAGE:----..----}␣LXCITE://
 Oberschelp:2007:Campani
```

```
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣%%IML:␣cite:␣NO␣␣20110000␣{
 LXK:Saturn;␣Saturn␣ring␣system;␣solar␣system;␣planets;␣
 discovery}␣{UDC:...}␣{PAGE:----..----}␣LXCITE://
 Oberschelp:2011:Campani
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣Giovanni␣Domenico␣Cassini␣later␣
 described␣the␣separation␣of␣the␣Saturn␣rings.
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣%%IML:␣cite:␣NO␣␣16740000␣{
 LXK:Saturn;␣Saturn␣ring␣system;␣solar␣system;␣planets;␣
 description}␣{UDC:...}␣{PAGE:----..----}␣LXCITE://
 Cassini:1674:Saturn
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣%%IML:␣cite:␣NO␣␣20070000␣{
 LXK:Saturn;␣Saturn␣ring␣system;␣solar␣system;␣planets;␣
 description}␣{UDC:...}␣{PAGE:----..----}␣LXCITE://
 Oberschelp:2007:Campani
␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣%%IML:␣cite:␣NO␣␣20110000␣{
 LXK:Saturn;␣Saturn␣ring␣system;␣solar␣system;␣planets;␣
 description}␣{UDC:...}␣{PAGE:----..----}␣LXCITE://
 Oberschelp:2011:Campani
```

Listing 4. Secondary citation reference set excerpt used with the UDC classified knowledge object "Saturn" (LX resources).

The secondary references from the knowledge resources refer to bibliographic objects, which resolve to [53] and [54]. From these references the tertiary references, in this case non-explicit references, refer to the knowledge resources documentation on Guiseppe Campani.

As shown, using the available features, e.g., the context categorisation from the knowledge resources it is possible to catch this information and to drastically increase the spectrum of gathering information and complementing the result matrix. The workflows and algorithms presented here can be used in order to overcome missing links in between different information pools and complement knowledge resources and workflows.

For a sustainable use of external "secondary" information any localisation and references data have to be long-term or medium-term persistent.

Currently, at least medium-term available methods have to be provided for consistent and reliable resources. This includes that the secondary data providers have to support at least concepts like URN (Uniform Resource Name), PURL (Persistent Uniform Resource Locator), DOI (Digital Object Identifier) instead of pure URL (Uniform Resource Locator).

In addition, for enabling citations and references, bibliographical data must be explicitly available as such with each reference. For long-term use this data it must be automatable, machine readable, and documented.

The current structure of the Leibniz archives' resources is explicitly not suitable for automated citation, referencing, and reuse. The sources themselves are currently distributed at several hosting institutions (e.g., Berlin, Hannover, Göttingen, Münster). For cases like these, it is recommended to implement a sustainable structure consistently over all the participated sources and to provide persistent references. Failures on the generated or provides references as shown above should be avoided in any case. All these aspects are issues, which should be seriously worked on by the Leibniz archives in order to create a sustainable future solution.

G. Flexible support for HEC and dynamical discovery

The KOA architecture is based on a flexible documentation and development architecture [29] and integrated with the case study implementations based on the Collaboration house framework for disciplines, services, and resources [28]. For the various HEC scenarios a flexible, scalable, and dynamical network solution, e.g., Software Defined Networks (SDN) is highly recommendable [55]. Building the tree paths as well as the discovery of connections in the carousels can be done in parallel, comparable to a modelling process. This way, while computing one tree it is possible to follow connections into other disciplines' branches interesting for a workflow. The task parallel processes can be computed to look ahead, dynamically discovering fitting relations. On the other hand, it is possible to compute multiple trees and create intermediate result matrices, which can be used for building multi-disciplinary results from a large number of trees.

H. Dynamical referencing

Referring objects for publicly available information can be integrated by dynamically building associations from the knowledge resources as has currently been done with search engine content, e.g., results from Google or other dynamical sources. Table VI shows the results of a Google search [56] done for the keywords "volcano, udc, classification". The results contain the UDC classification found with the request as well as the terms associated with this in the text.

Table VI. VOLCANO RESULTS FROM PUBLICLY AVAILABLE INFORMATION, GOOGLE SEARCH, STATUS OF JANUARY 2013 (EXCERPT).

UDC Classification	*In-text Terms*
551.442(437.6)	Volcano, phreatic
631.4	Volcano
553.405	Uranium, deposit, volcano
551.31:551.44(532)	Volcano
(*764)	Volcano
(*7)	Volcano

Table VII shows the results of a Google search done for the keywords "cenote, udc, classification".

Table VII. CENOTE RESULTS FROM PUBLICLY AVAILABLE INFORMATION, GOOGLE SEARCH, STATUS OF JANUARY 2013 (EXCERPT).

UDC Classification	*In-text Terms*
930.85(726.6) 551.435.8:528.9	Sinkhole cenote maya
551.44	Doline, sinkhole
556.34:519.216	Sinkhole, drainage
551.435.82(234.41)	Sinkhole, collapse
624.153.6:699.8:551.448	Sinkhole, collapse
551.44(450.75)	Karst, sinkhole, collapse
551.44(045)=20	Groundwater, surfacewater
551.44:001.4	Grotte, Höhle
551.44(450.75)	Karst, Apulia
551.44(437.2)	Geology, karst

All documents found from public external sources in this context have been identified to contain academical and scientific content. Even as this example is intended to provide a lower depth of knowledge mapping than available in specialised knowledge resources, it provides an excellent spectrum of related information for the respective disciplines. There should be emphasis on the fact that this kind of classification on material in manually added to the content by the creator. After considering material of this kind for a knowledge discovery process an automated classification can be computed from the content independently by any service. Both types of classification can contribute in order to obtain a case-optimised result matrix at any step within the discovery workflow.

I. Workflow and computation demands

Table VIII shows the resulting computation times (wall clock) for straight and broadened application qualities. per workflow instance and request. Requests are restricted to three initial terms. Straight means calculating the result matrix directly from the plain data available, including ranking. Broadened means using full text, references, and available secondary context information, with a wide spectrum of topics. It is possible to flexibly support the knowledge discovery workflow by any number and kind of algorithms and communication. In this case classification, keywords, synonyms, phonetic algorithms, homophones, and category lists have been used.

Table VIII. STRAIGHT AND BROADENED (SERIAL) APPLICATION QUALITIES AND COMPUTATION TIMES PER WORKFLOW INSTANCE AND REQUEST (RESTRICTED TO THREE INITIAL TERMS).

Item	*Straight*	*Broadened*
Number of terms (restricted for demo.)	3	3
Comparisons	$\approx 90,000$	$\approx 1,090,000$
Selection processes	1,540	16,700
Intermediate results	420	5,100
Final results (selected top 10)	10	10
Classification evaluation time share	3 s	30 s
Keyword extraction time share	2 s	4 s
Fulltext support time share	4 s	22 s
Reference support time share	1 s	3 s
Phonetic support time share	3 s	8 s
Instance computation time	3 s	120 s

The example demonstrates the principle and tendency. Starting a single workflow instance with a small number of 3 object terms (Figure 5), this statistically results in:

a) *Straight*: Retrieval followed by 90,000 comparisons, delivers 30,000 results, ranked to create a top 10.
b) *Broadened*: This requires an additional 1 million comparisons per term and some 10,000 comparisons on more than one term as well as on subterms, it delivers 90,000 results, which are ranked to create a top 10.

In an average of terms, b) results in 3 new top terms better reflecting the context, which means a significant improvement of the quality of the result matrix. As Table VIII shows, when improving the quality, the compute time increases from about 3 seconds to 2 minutes. Over the time the resource usage increases by about a factor of 50. Due to the structure of the compute algorithms a part of the workflow processes can be done in parallel before the final result matrix is created. Other advanced workflow processes, e.g., those processes where all the intermediate results must be available before any decision on the next step can be done, have to be chained for the purpose of improving the quality. With parallel processing in the above example the overall time can be reduced to about 30 s on the same architecture if an increased number of resources is available. Increasing the number of comparisons by adding further sources for improving the quality of results increases the requirements on resources more than linear referring to the compute time. This is going ahead with a smaller amount of numerical improvement for the top results. The knowledge resources fully support this procedure. The broadened serial and task parallel (dual-core processors) application qualities per workflow instance and request are summarised in Table IX.

Table IX. BROADENED SERIAL AND PARALLEL APPLICATION QUALITIES PER WORKFLOW INSTANCE AND REQUEST (AS ABOVE).

Workflow Item	*Broadened Serial*	*Broadened Parallel*
Number of terms (restricted for demo.)	3	3
Parallel resources (nodes)	1	10
Instance computation time	120 s	20 s

The resulting computation times per instance can be efficiently reduced exploiting parallelity of resources. Modularising the knowledge resources into dynamical entity groups of objects is very efficient for a large number of requests and resources available. This is especially interesting for any wider economical and practical interactive use. The higher the complexity of the single, even non-linear, workflow is, the less efficient are todays resources architectures.

X. EVALUATION AND DISCUSSION

The results from the work and case studies presented in this paper have shown that for a higher understanding of the contributions the various implementations cannot be separated but should be considered complementary. The implemented

... concepts and structures correspond with the methodology and systematics.
... content presents the results achieved by precise sciences and their application.
... means for documentation, discovery, and computation are done exemplarily for the knowledge resources.
... universal classification views and references show the logical integration.
... components show the flexibility and extendability.
... case studies show the practical use.

The long-term multi-disciplinary focus has been sustainability, expenses and benefits, and complementary results.

A. Sustainability

Regarding the sustainability of the knowledge resources support it has been practical to consider three main aspects for creating sustainable KOA architectures.

1) *Scalability and efficiency:* The workflow process can be modularised and therefore can be implemented as scalable and parallelised algorithms.

2) *Discovery and content:* Big amounts of multi-disciplinary information will always have to consider inhomogeneous groups of information. With the described method the barrier between the inhomogeneous content, for example, between different disciplines can be overcome. The knowledge resources support structuring and modularising the workflows to a defined level. Any references that might not already exist explicitely in the knowledge resources can be suggested by a non-tree link. An example is, computing full text comparisons between the carousels from the available plain content of the knowledge resources.
3) *Universal multi-disciplinarity:* The knowledge resources allow any number of dimensional space. Besides that, the knowledge resources allow to use multi-disciplinary clustering of objects, e.g., clustering of stones for an archaeological view as well as for a petrographical view.

These features can be used for a flexible dynamically guided discovery. Besides the benefits of very flexible classification support, e.g., via UDC, expenses are that the creation and operation do require intensive work.

B. Expenses and benefits

Classification support, e.g., via UDC, does require intensive work, is expensive, and very much profits from professional experiences. The application of UDC with complex knowledge needs flexibility of the resources as wells as a flexible handling in extendability. The challenges with the distributed use of UDC are, e.g., the use of private catalogues, like external codes or author abbreviations. In addition, the sustainability of knowledge objects will benefit from the use of methods like facetted versioning, universal dates (e.g., ISO dates), and georeferencing.

C. Complementary results

With the presented object carousels an undefined number of practical workflows can be created on the knowledge resources. Examples, which have been investigated for gathering complementary results are regular expression and string search, classification search (UDC), keyword search, sort support search, references search or phonetic search (Soundex).

D. Information and classification

Text information and classification information are complementary. This is important for knowledge resources as well a for application scenarios, e.g., search algorithms. Using classification supported search algorithms can improve the result drastically. The quality of results improves from below five percent to up to over ninety percent.

XI. Conclusion and Future Work

Structuring and classification with long-term knowledge resources and UDC support have successfully provided efficient and economic base for an integration of multi-disciplinary knowledge and IICS components, supporting archaeological and geoscientific information systems. With these, the solution is scalable, e.g., regarding references, resolution, and view arrangements. The concept can be transferred to numerous applications in a very flexible way. The overall results on object carousels and Q4Q workflows from the implementation and case studies are:

- The quality of data can be most efficiently improved at the knowledge resources components.
- The quantity of data can be increased by referencing and intelligent discovery workflow algorithms.
- The quantity of compute and storage resources is both tightly linked with the quality of data and the quantity of data and resources requirements.

The knowledge resources can be integrated into a steadily improving system architecture storing data for successful creation of sustainable workflow definitions, meaning that the result matrix of requests can be stored for future use and evaluation. This can be done in a non-incremental way, depending on the environment of communication, computation, and storage resources in order to provide an efficient solution. Separate snapshots of the knowledge resources allow to consider developments within time. Nevertheless, for service operation this can result in very high computational requirements for resources.

Integration of external information resources has shown huge benefits on the quantity of data. The quantity can be used for creating higher quality result matrices and improve the discovery. A number of recommendations have been given for integrating external data into advanced knowledge resources. Future developments of the external resources should consider to comply with a systematic, consistent, and well structured base for their data, interfaces, and publications.

With the presented object carousels an undefined number of practical workflows can be created on the knowledge resources. The object carousels concept is part of the "tooth system" for long-term documentation and algorithms and the exploitation of supercomputing resources for use with future IICS. Work has been done [57], [58] in order to facilitate that future architectures and components will support intelligent system components and processing modelling of complex environments.

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