Sustainable Knowledge Resources Supporting Scientific Supercomputing for Archaeological and Geoscientific Information Systems

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***Abstract*—This paper presents the results from an implementation of long-term sustainable knowledge resources, which can be used for documentation, classification, and structuring as well as with scientific supercomputing resources for advanced information systems. The paper discusses the current implementation of information structures and object representations used with universal classification and computation algorithms for multi-disciplinary, dynamical knowledge discovery. It discusses practical examples from archaeology and geosciences disciplines, relying on the content, structure, and classification from the knowledge resources used with various case studies. The combination of universal knowledge resources and computational workflows based on High End Computing (HEC) resources and Universal Decimal Classification (UDC) allows for the goal of successful creation of long-term sustainable Integrated Information and Computing System components.**

***Keywords*–Integrated Systems; Scientific Supercomputing; Sustainability; Knowledge Resources; Information Systems; UDC; Archaeology; Geosciences; High Performance Computing.**

I. Introduction

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. The knowledge resources should not only be traditional collections as with digital libraries [1] and isolated content [2] 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 [3], [4].

So, this decisively contributes to the goal of successful creation of long-term sustainable Integrated Information and Computing System components. 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 [5]. 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 Integrated Information and Computing System (IICS) components [6]. Multi-disciplinary knowledge resources are used to resemble and document of any information available. As the requirements for complexity can become arbitrary high, compute resources have to be used for any more advanced applications. Creating workflows based on the multi-disciplinary knowledge matrix therefore requires highly performant 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. 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 present a practically used classification approach to the challenges. Sections VI and VII describe the new concept of object carousels, the discovery of “missing links”, workflow, and computation demands. Sections VIII and IX discuss the lessons learned and summarise conclusions and future work.

II. Sustainability and vitality

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. With the

 ISBN: 978-1-61208-310-0

available systems components, we have Resources Oriented Architectures (ROA), Services Oriented Architectures (SOA), and “Knowledge Oriented Architectures” (KOA) in addition [7]. 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.

III. Complex knowledge resources case

The knowledge resources created can integrate any object. These objects can be described with universal classification, handled with phonetic algorithms [8], [9], and can refer to external 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”.

IV. Knowledge resources classification support

The operated knowledge resources, based on the LX Foundation Scientific Resources [8], incorporate UDC classification for any discipline and purpose, e.g., for knowledge discovery and workflows. Practical summarising excerpt subsets for specific disciplines are given in Tables I to II.

Table I. Archaeology knowledge resources classification.

UDC Code	*Description*
UDC902	Archaeology
UDC903	Prehistory. Prehistoric remains, artefacts, antiquities
UDC904	Cultural remains of historical times
UDC”63”	Archaeological, prehistoric, protohistoric periods, ages
UDC56	Palaeontology
UDC55	Earth Sciences. Geological sciences
UDC711.42	Kinds of town, locality, settlement
UDC720.32	Ancient architecture

Table II. Volcanoes knowledge resources classification.

UDC Code	*Description*
UDC532	Fluid mechanics in general.
UDC550.93	Geochronology. Geological dating. . . .
UDC551	General geology. Meteorology.
UDC551.1	General structure of the Earth
UDC551.2	Internal geodynamics (endogenous processes)
UDC551.21	Vulcanicity. Vulcanism. Volcanoes. Eruptive phenomena.
UDC551.23	Fumaroles. Solfataras. Geysers. Hot springs. Mofettes.
UDC551.24	Geotectonics
UDC551.26	Structural-formative zones and geological formations
UDC551.4	Geomorphology. Study of the Earth’s physical forms
UDC551.44	Speleology. Caves. Fissures. Underground waters
UDC551.462	Submarine topography. Sea-floor features
UDC551.588	Influence of environment on climate
UDC551.7	Historical geology. Stratigraphy
UDC551.8	Palaeogeography
UDC552.2	General petrography. Classification of rocks

The UDC sets have been used with the presented computation. UDC [10] currently provides around 70000 entries in about 100 top classes, whereas the UDC Summary [11] provides a selection of more than 2000 classes. The multilingual support lists translations in fifty languages [12]. UDC classifications have been integrated with tens of thousands of knowledge objects [9] which are a base for each computation.

V. 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 [13]. In many multi-disciplinary cases, e.g., explicitely shown with the case studies [6], [8], 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.

VI. 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

 ISBN: 978-1-61208-310-0

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.

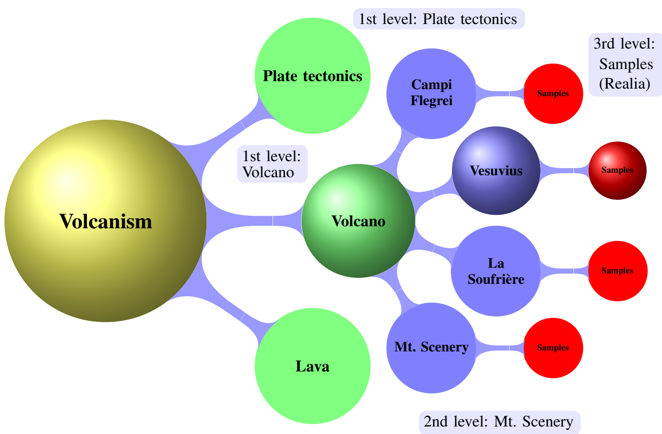

Figure 1. Object carousel for terrestrial "volcanism" context with subset of computed volcano references and examples of levels object relations.

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 [5] 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 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

 ISBN: 978-1-61208-310-0

(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.

VII. 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 3). 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 3 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 III shows an excerpt of attributes and examples.

Table III. 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.

C. Flexible support for HEC and dynamical discovery

The KOA architecture is based on a flexible documentation and development architecture [9] and integrated with the case study implementations based on the Collaboration house framework for disciplines, services, and resources [8]. 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. 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.

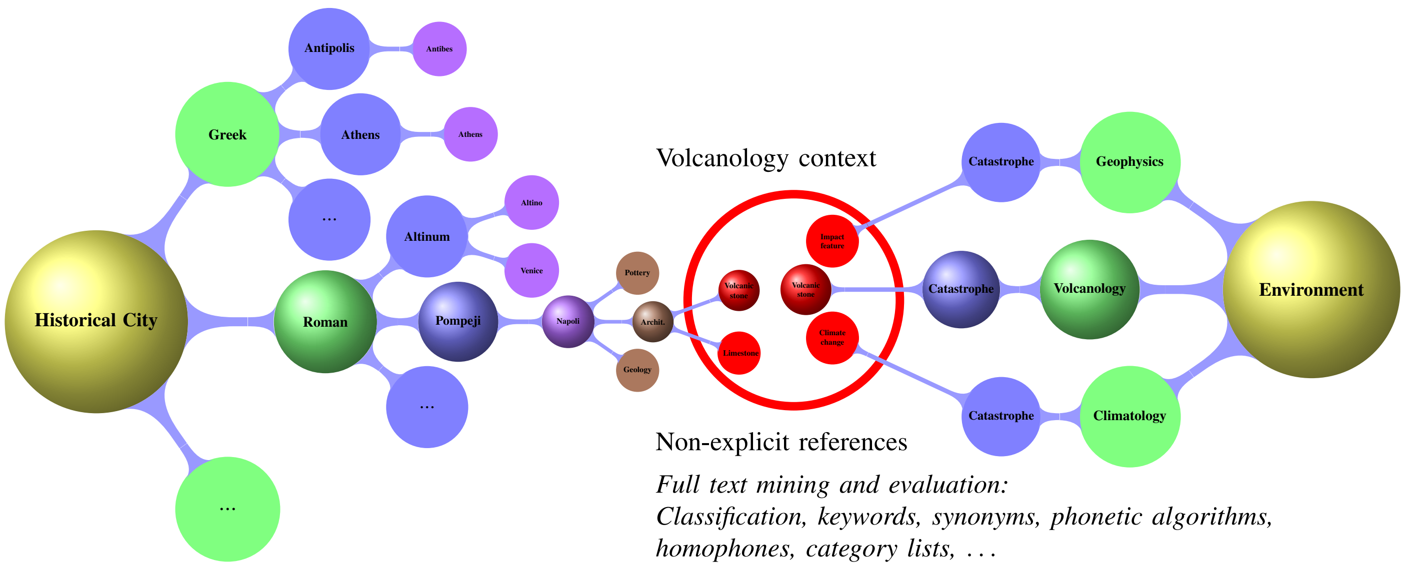

Figure 3. Computing object carousel connections: Historical city and environment object carousels showing trees with a subset of computed references. In this sample workflow the carousel links are calculated via non-explicit references of comparable objects (red) from knowledge resources within trees.

D. Workflow and computation demands

Table IV shows the resulting computation times (wall clock) for straight and broadened application qualities. 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 IV. 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	≈ 90000	≈ 1090000
Selection processes	1540	16700
Intermediate results	420	5100
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 3), this statistically results in:

a) *Straight*: Retrieval followed by 90000 comparisons, delivers 30000 results, ranked to create a top 10.

b) *Broadened*: This requires an additional 1 million comparisons per term and some 10000 comparisons on more than one term as well as on subterms, it delivers 90000 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 IV 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 V.

Table V. 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.

VIII. Discussion

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.

IX. 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 requirements for resources. 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.

Acknowledgements

We are grateful to all national and international partners in the GEXI cooperations for the innovative constructive work. We thank the Science and High Performance Supercomputing Centre (SHPSC) for long-term support of collaborative research since 1997, including the GEXI developments and case studies on archaeological and geoscientific information systems. Thanks go to the scientific colleagues at the Institute for Legal Informatics (IRI), Leibniz Universität Hannover, and WWU Münster, as well as to the participants of the EULISP Programme for prolific discussion of scientific, legal, and technical aspects over the last years.

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