Methodology and Integrated Knowledge for Complex Knowledge Mining: Natural Sciences and Archaeology Case Study Results

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***Abstract*—This paper presents a new methodology for advanced knowledge mining, improving complex discovery and decision making results and providing potential for creating new insights. The paper provides the results of the present research and from an implementation and a case study. The case study utilises topics, techniques, and data from geosciences, archaeology and multi-disciplinary context. The methodology is using integrated knowledge resources for complex knowledge mining by creating workflows applying specialised tools. The resulting methodology can be applied with any disciplines and with combinations of general, as well as specialised tools. The results of the knowledge mining can be used for gaining insight and creating automated learning processes, especially with long-term knowledge resources, which are continuously in development. The goal of this research is to create new practical mining procedures, gain insight and further develop available multi-disciplinary knowledge resources.**

***Keywords*–Data-centric Knowledge Mining; Knowledge Resources; Integrative Methodology; Universal Decimal Classification; Advanced Computing.**

I. Introduction

This research is focussed on the integration of knowledge resources referring to universal classification and application components for solving complex tasks, e.g., for knowledge mining. Target of the research is a methodology integrating knowledge resources and specialised application components for a gain in knowledge, cognition, and insight. The integration of knowledge discovery and decision making processes can result in extremely challenging tasks.

The quality of results from knowledge mining is primarily connected with content and algorithms. The language or method used for expressing a 'question' and automating its translation in general is not of concern for this research. Data resources, whatever their size is, do not automatically deliver high quality results. In most cases, content and algorithms are limiting possibilities to answer complex and staggered questions in reasonable ways. Contributions to these deficiencies result from data, algorithms, and their implementations. Therefore, high quality knowledge resources, including factual, conceptual, procedural, and metacognitive knowledge, description, and documentation are increasingly important. In consequence, advancing methodologies for knowledge mining is in the focus with comparable importance.

Several disciplines contribute and specialised approaches and solutions have to be used on context for coping with any slightly complex question. Built on such in-deficit foundation, there is no direct and common practice on how to integrate specialised algorithms and applications with each other without a methodology. Appropriate methodologies will allow to integrate advanced knowledge resources and to modularise several tasks within a knowledge mining workflow.

The motivation for this research results from the unsatisfactory and non-knowledge centric instruments available. For many knowledge mining challenges, e.g., seeking good answers to complex questions, there are no solutions available for integrating complex knowledge resources and arbitrary application components. A sample question is:

Which natural events associated with the creation of crater structures with a diameter larger than 100 m could have been directly notable by human population within the last thousands of years and are still observable on-land at the area of todays' continent of Europe and which knowledge is associated with such events?

The question is quite precise but present possibilities mostly cannot achieve appropriately precise results in order to answer such questions. If one is not satisfied with arbitrary lists of hundreds of snippets of information mostly not part of an answer instead of an on-topic result then we have to find better ways. A solution is to flexibly integrate high quality data with conceptual knowledge and suitable application components with appropriate features.

This paper is organised as follows. Section II introduces the methodology applied for knowledge mining. Section III discusses implementation and case study, resulting references and associations, and the workflow implementation. Section IV discusses the results from the application of the methodology and implementation, based on previous work and re-usable components. Section V summarises the lessons learned, conclusions, and future work.

II. Methodology

With this research, a methodology is defined by a sequence of steps. The steps can be a set of procedures in order to create a result for a knowledge mining process, e.g., with a discovery process. The procedures can include data, knowledge, formal descriptions, and implementations, e.g., collecting data, retrieving information, and algorithmic specifications. The purpose can range from delivering to creating and answer to an open question, e.g., delivering knowledge for a learning or decision making process. The methodology uses a formal description

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of knowledge, data and information, as well as required research techniques. Content and context are represented by any knowledge objects and data available in time and space. Data may be structured and unstructured.

1a) Identification of a knowledge mining challenge.
1b) Phrasing of a problem or question.
1c) Identification of a solution or answering strategy.
1d) Context description and modeling.
1e) Mapping of sub-challenges to possible partial solutions.
1f) Interface creation for partial solutions.
2a) Creation and / or selection of cogwheel modules (modularisation into sub-challenges and partial solutions).
2b) Knowledge and information: Identification or creation and / or selection of nuclei and facets.
2c) Peeling of information-nuclei from existing evidence.
2d) Milling of nuclei.
2e) Information processing.
2f) Data selection including nuclei and facets.
2g) Information object turnaround.
3a) Workflow implementation (incl. cogwheel modules).
3b) Analysis of results.
3c) Learning process and persistent documentation.
3d) Improvement process.

We can identify three main groups within the methodology. 1a) to 1f) is a preparatory phase, 2a) to 2g) describes a gearbox of knowledge mining, and 3a) to 3d) is a consecutive phase.

The modules allow to assign specialised applications and specialised features to separate modules as will be shown in the following implementation. Options and features of specialised applications can be documented, including conceptual knowledge, with the learning process and to cope with reoccurring requirements. The methodology allows to create different approaches for a workflow.

III. Implementation and Case Study

The methodology was applied to practical situations. The following case study presents a practical workflow implementation based on the above gearbox of knowledge, including the required cogwheel modules with their mapping to important components and steps, their implementation and results.

The starting point is the above sample question. The required compositions of features and criteria can become quite complex and are commonly not implemented in any single application or component. Therefore, the integration of appropriate application components can be desireable or even required.

The plethora of information from the knowledge resources is narrowed by the conceptual knowledge, the references to classifications, e.g., to the mapping and data of:

- Craters (any, e.g., Earth and other planets),
  - volcanic features including craters,
  - impact craters including meteorites, ...
- confirmed (and non-confirmed) structures/craters,
- structures observable on-land,
- age less than (about) 9999 years old,
- larger than 100 m diameter.

The respective workflow requires a number of special calculations as well as criteria cogwheel modules for knowledge resources and spatial components.

Applying a universal classification can be used to classify the appropriate objects, the associated application components, and the respective required options for a cogwheel module, e.g., for the calculations and filters.

In this case, the two groups of components involved with creating a solution are a) advanced knowledge resources and b) knowledge mining including conceptual knowledge references, spatial data and applications.

The definition of data-centricity used is: "The term data-centric refers to a focus, in which data is most relevant in context with a purpose. Data structuring, data shaping, and long-term aspects are important concerns. Data-centricity concentrates on data-based content and is beneficial for information and knowledge and for emphasizing their value. Technical implementations need to consider distributed data, non-distributed data, and data locality and enable advanced data handling and analysis. Implementations should support separating data from technical implementations as far as possible." [1]. According to this, the implementation of the methodology is as far data-centric as possible and allows a systematic application.

The following sections describe the essentials of the cogwheel modules required, including the handling of the nuclei and information processing. The sub-challenges are presented with their mapping to applications. Relevant excerpts of data and information are discussed in anticipation of the final results. The concluding section shows the workflow implementation used for creating the final results.

A. *Multi-disciplinary knowledge resources identification*

The knowledge resources hold arbitrary multi-disciplinary knowledge (e.g., documentation of factual, conceptual, procedural, and metacognitive knowledge), in various structures as well as unstructured, objects, and references, including information on digital objects and realia objects, e.g., media objects and archived physical specimen. These resources provide the prerequisites in order to create efficient cogwheel modules and handle knowledge and information nuclei and facets for peeling and milling processes.

1) Factual knowledge: The knowledge resources also contain information on various types of crater features like volcanic craters and impact craters. Especially, the Earth's impact crater container in the knowledge resources container holds data and references for all known impact craters on Earth.

The impact features container holds the Kaali impact, represented by its major impact crater. The minor craters of this impact event are referenced from this object and form sub-objects, all of which contain their factual and referenced data.

Figure 1 shows a spatial presentation of terrestrial (meteorite) impact features resulting from the impact features container. The multi-disciplinary knowledge resources were used to create various computational views of impact craters on Earth [2]. The multi-disciplinary views, including conceptual classifications, enable an association of various characteristics common with different collection information [3].

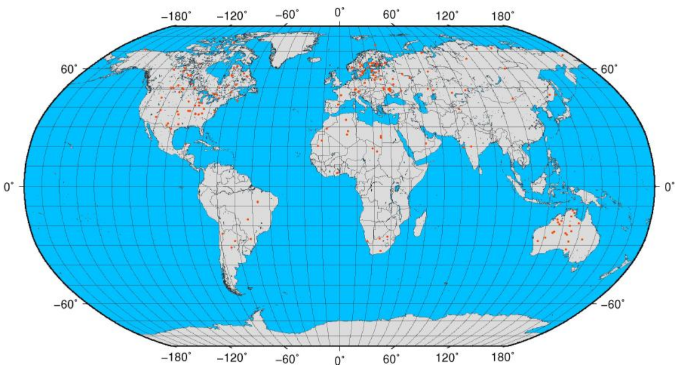

Figure 1. Impactmap – computed worldwide spatial distribution of classified terrestrial impact features (meteorite) from available object entries.

In this case, Earth surface information, georeferenced geophysical and geological factual data, have been associated.

Table I lists the factual container data used from the LX Foundation Scientific Resources [4] referenced for the Kaali crater field object and relevant with the mining challenge.

TABLE I. RESULTING FACTUAL DATA REFERENCED FOR THE KAALI CRATER FIELD (EXCERPT, LX RESOURCES).

Crater Number	*Coordinates (lat/lon)*		*Diameter (m)*	*Elevation (m)*
1	58.371270	22.664737	39	24.10
2	58.367407	22.672298	25	25.90
3	58.366556	22.677637	76	21.99
4	58.371982	22.675092	33	24.91
5	58.370815	22.675611	20	21.90
6	58.370861	22.663155	13	29.90
7	58.370306	22.671848	26	22.90
8	58.367460	22.672577	15	25.99
9	58.372715	22.669419	110	34.14

The crater field consists of 9 known craters. Crater number 9 is the major crater. Craters 1 to 8 form sub-container objects, which deliver the data.

2) Conceptual knowledge: Advanced knowledge from integration of universal classification and spatial information can provide new insights when applied with knowledge mining [5]. The use of the Universal Decimal Classification (UDC) is widely popular, e.g., in library context, geosciences [6], and mapping [7] as provided by the Natural Environment Research Council (NERC) [8] via the NERC Open Research Archive (NORA) [9]. The small 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) [10] released by the UDC Consortium under the Creative Commons Attribution Share Alike 3.0 license [11] (first release 2009, subsequent update 2012). Data in the knowledge resources carries references to classifications, e.g., UDC, for any discipline and object, e.g., natural sciences and history. Here, besides the central UDC:539.63 (impact effects) and UDC:539.8 (other physico-mechanical effects), referred top level groups for geodesy, cartography, and geography are UDC:528 [12], UDC:910 [13], and UDC:912 [14]. Tables II and III show excerpts of the conceptual data (UDC) used for geodetic / cartographic and geographic classification.

TABLE II. CLASSIFICATION WITH KNOWLEDGE RESOURCES: GEODETIC AND CARTOGRAPHIC CONCEPTUAL DATA (LX).

UDC Code	*Description (English, excerpt)*
UDC:5	MATHEMATICS. NATURAL SCIENCES
UDC:52	Astronomy. Astrophysics. Space research. Geodesy
UDC:528	Geodesy. Surveying. Photogrammetry. Remote sensing. Cartography
UDC:528.4	Field surveying. Land surveying. Cadastral survey. Topography. Engineering survey. Special fields of surveying
UDC:528.5	Geodetic instruments and equipment
UDC:528.7	Photogrammetry: aerial, terrestrial
UDC:528.8	Remote sensing
UDC:528.9	Cartography. Mapping (textual documents)

TABLE III. CLASSIFICATION WITH KNOWLEDGE RESOURCES: GEOGRAPHIC CONCEPTUAL DATA (LX).

UDC Code	*Description (English, excerpt)*
UDC:9	GEOGRAPHY. BIOGRAPHY. HISTORY
UDC:91	Geography. Exploration of the Earth and of individual countries. Travel. Regional geography
UDC:910	General questions. Geography as a science. Exploration. Travel
UDC:910.2	Kinds and techniques of geographical exploration
UDC:912	Nonliterary, nontextual representations of a region

Composite classification based on these top level classification references can refer to special items, e.g., cartographic bibliographies, historical atlases, and globes. Summarised, the classification can be used as glueing component classifying the knowledge object space and the implementation space, e.g., respective resources, objects, application components, and features of application components. This also provides the base for the creation of conceptual knowledge objects.

B. Geoscientific data and components mapping

Appropriate data was required for the topographic data related criteria. In the past, the georeferenced objects have been used with various data, e.g., with the Global Land One-kilometer Base Elevation Project (GLOBE) [15] and the 2-minute gridded global relief data (ETOPO2v2) [16].

For the required resolution of the results presented here, the knowledge resources had to be integrated with data based on the gridded ETOPO1 1 arc-minute global relief model data [17]. For special purposes data can be composed from various sources, e.g., adding Shuttle Radar Topography Mission (SRTM) data [18] from the Consultative Group on International Agricultural Research (CGIAR) [19].

The horizontal datum of ETOPO1 is World Geodetic System geographic, which was established in 1984 (WGS84) and later revised. The WGS84 specifications and references are provided by the National Geospatial-Intelligence Agency (NGA) [20] and as EPSG:4326 from the European Petroleum Survey Group Geodesy (EPSG) [21]. The vertical datum of ETOPO1 is “sea level”. The source elevation data were not converted by the authors of ETOPO1 to a common vertical datum because of the large cell size of 1 arc-minute.

The Generic Mapping Tools (GMT) [22] suite application components are used for handling the spatial data, applying the related criteria, and for the visualisation.

C. Peeling and milling of context references

The knowledge resources provide references to multi-disciplinary knowledge, e.g., photo media objects related to an object. Examples are objects referred by conceptual knowledge and contextual knowledge references (Figure 2).

```
Photo-Object: Birgit Gersbeck-Schierholz, Hannover, Germany.
media: YES 20160629 {LXC:DETAIL--M-} {UDC:(0.034)(044)770} LXDATASTORAGE://...
 kaali2016_1.JPG ...
media: YES 20160629 {LXC:DETAIL--M-} {UDC:(0.034)(044)770} LXDATASTORAGE://...
 kaali2016_2.JPG ...
media: YES 20160629 {LXC:DETAIL--M-} {UDC:(0.034)(044)770} LXDATASTORAGE://...
 kaali2016_3.JPG ...
media: YES 20160629 {LXC:DETAIL--M-} {UDC:(0.034)(044)770} LXDATASTORAGE://...
 kaali2016_4.JPG ...
media: YES 20160629 {LXC:DETAIL--M-} {UDC:(0.034)(044)770} LXDATASTORAGE://...
 kaali2016_5.JPG ...
Object-Discoverer: Birgit Gersbeck-Schierholz, Hannover, Germany.
Photo-Object: Claus-Peter Rückemann, Minden, Germany.
media: YES 20160629 {LXC:DETAIL--M-} {UDC:(0.034)(044)770} LXDATASTORAGE://...
 img_0086.jpg
```

Figure 2. Information peeling: Media entries from knowledge resources objects (multi-disciplinary geosciences collection, LX, excerpt).

The excerpt shows referenced media for “Kaali crater” after the peeling process from the object. The excerpt of an object associated with a knowledge object is shown in Figure 3.

```
Lilium ... [Biology, Botany]:
           (lat.) Lilium martagon.
           Earth mull vegetation.
           Indicator: Eutrophic, leach enriched, clayey and loamy soils, shadow
            and penumbra location.
           ...
           Syn.: Türkenbundlilie
           Syn.: martagon lily
           Syn.: Turk’s cap lily ...
```

Figure 3. Information peeling of Lilium martagon knowledge resources object (multi-disciplinary geosciences collection, LX, excerpt).

The excerpt shows an object “Lilium martagon” associated with the “Kaali crater” object after the information peeling process from this object. Figure 4 lists an excerpt of associated bibliographic references for an object.

```
cite: YES 20070000 {LXK:Kaali Kraater; Kaali crater; meteorite; impact} {UDC:
 ...} {PAGE:----..----} LXCITE://Tiirmaa:2007:Meteorite
cite: YES 20160000 {LXK:Kaali Kraater; Kaali crater; meteorite; impact} {UDC:
 ...} {PAGE:----..----} LXCITE://Tiirmaa:2016:Scars
cite: YES 20120000 {LXK:Kaali Kraater; Kaali crater; meteorite; impact;
 Excalibur; sword} {UDC:...} {PAGE:----..----} LXCITE://Faure:2012:Estonians
cite: YES 20160000 {LXK:Kaali Kraater; Kaali crater; meteorite; impact;
 Tutankhamun; dagger} {UDC:...} {PAGE:----..----} LXCITE://
 Comelli:2016:Tutankhamun
```

Figure 4. Information peeling: Citation entries from knowledge resources objects (multi-disciplinary geosciences collection, LX, excerpt).

The referenced citation entries are the result of the information peeling process from the Kaali crater object and refer to bibliographic references for meteorite craters on the island of Saaremaa [23] as well as to meteorite craters in Estonia [24].

Other references point to information for meteorite-material-usage, e.g., in context with archaeological and historical or mythical context like King Arthur’s sword Excalibur (‘Ex-Kali-bur’) [25] directly associated with Kaali (mother goddess Kali) and its metal material and via association of sword synonyms and metal object classification to Tutankhamun’s dagger [26] (made with meteorite iron from Egypt).

D. Workflow implementation and phases

For the case study, the required data and configuration is selected manually for the preparatory phase. The consequent modules act on base of that data, especially conceptual knowledge and factual knowledge. The central cogwheel module `cogwheel_criteria` in the knowledge mining gearbox utilises a sequence `lximpactsselect_crae_criteria` containing a number of components

1) `lximpactsselect_crae_date`
2) `lximpactsselect_crae_confirmed`
3) `lximpactsselect_crae_age_historic`
4) `lximpactsselect_crae_diameter`

for handling the criteria for the event date range, confirmed and not confirmed events, the date range, and the crater diameter. In this case the components can be considered as filter processes.

The spatial modules of the workflow (`cogwheel_world`, `cogwheel_region`) utilise the features latitude and longitude, wet / land criteria, criteria evaluation, spatial distance computation, map projection, and visualisation. The respective components are provided by GMT suite applications, especially `pscoast` and `gmtselect`. The GMT applications have to care for longitude, latitude, elevation and contribute to the applying topographical data related criteria, for topography related decision making within the information object turnaround.

The later association of knowledge objects, referenced media objects, and citation objects is supported by conceptual knowledge and discovery processes. In the consecutive phase results are analysed and persistently documented in order to improve the knowledge resources and mining algorithms.

IV. Final results and discussion

Earths’ impact crater objects from the classified LX factual knowledge resources are used as a factual and conceptual knowledge source for computing results, considering the respective context and selection criteria. Result can be a group of craters, fitting to all the criteria, after the mining algorithm is applied to the integrated knowledge resources and methods.

A. Result of implemented workflow

Figure 5 shows the resulting output, including the necessary topography (longitude, latitude, elevation), data, and information used, after the result was visualised via GMT. Criteria for decision making are the resulting target structures (meteorite craters) on land (topography and coverage), especially confirmed Earth crater groups (meteorite impact features, bullets, red, blue, and green colours), age and size of (on-land) structures, and a reasonable catchment area for Europe (blue),

A catchment center has been choosen, a circular area with a respective radius of 3000 km, automatically fitted with the map projection. The blue circle marks a reasonable area to cover the continent of Europe in this context. The blue and green bullets mark the craters inside that area. The data, items, and marks are automatically computed and visualised.

The final resulting object (bullet, green colour), which fits all criteria is the Kaali crater field, Saaremaa, Estonia. The region of positive final result of the applied knowledge mining is computed and presented via GMT, too. Figure 6 shows the region of the Kaali crater field on the island of Saaremaa, Estonia in its topographic context.

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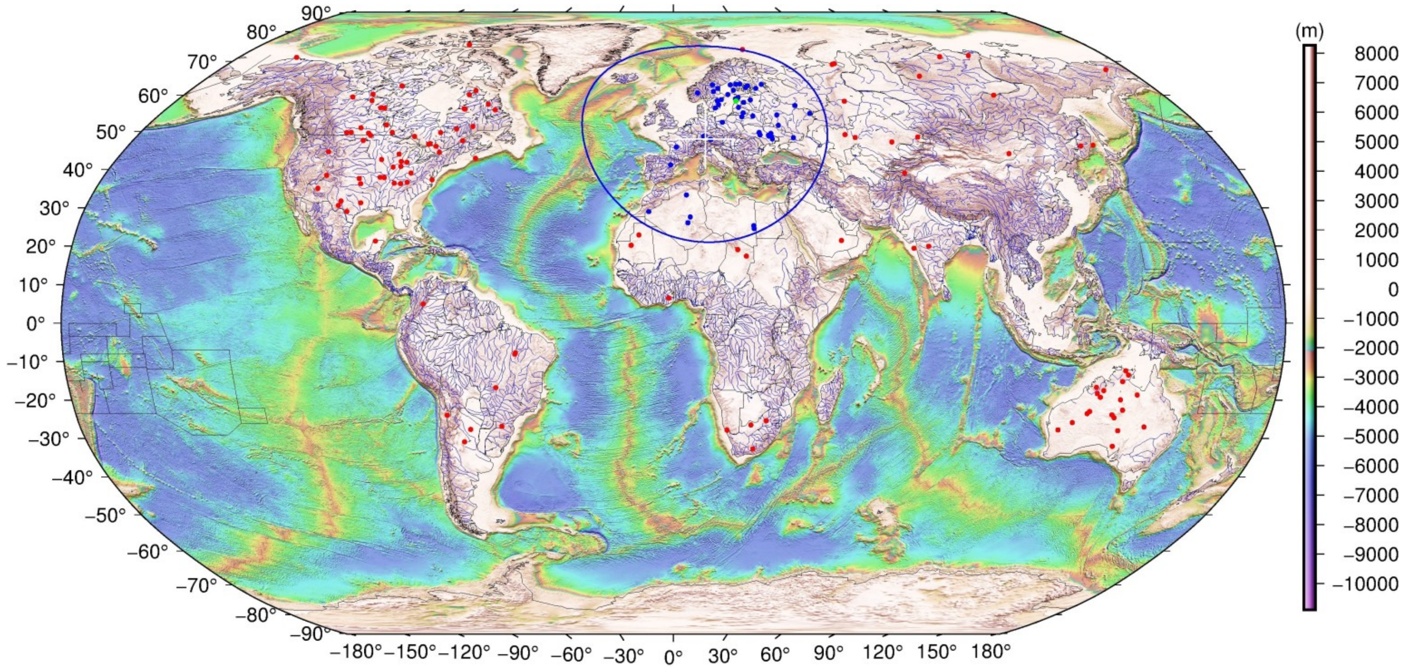

Figure 5. Knowledge mining methodology applied (LX factual and conceptual knowledge, factual data). Criteria are resulting crater groups (meteorite impacts, all coloured bullets), age and size of (on-land) structures, area, topography (all coloured bullets). Final result: Kaali crater field (green), Saaremaa, Estonia.

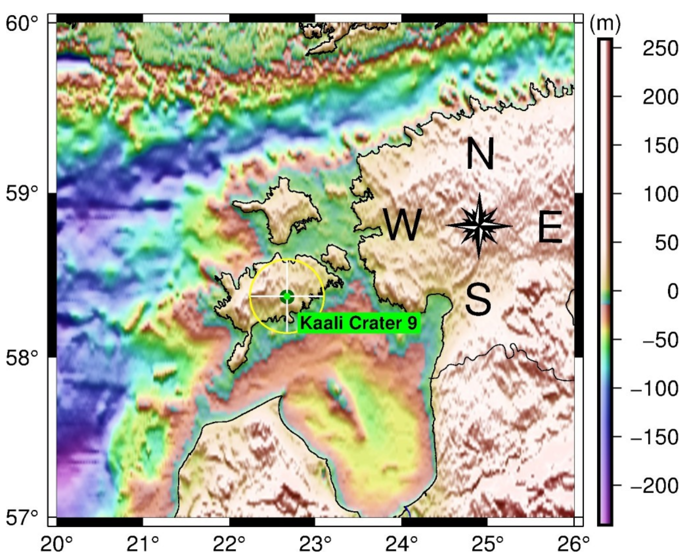

Figure 6. Detail of final result of knowledge mining in topographic context: Region around center of Kaali crater field, Saaremaa, Estonia

The bullet and the cross mark the center of the crater field (labeled Kaali Crater 9). The yellow ring marks an area of 25 km around the major crater.

B. Resulting associated information: Spatial mapping

The Keyhole Markup Language (KML) is an eXtended Markup Language (XML) based format for specifying spatial data and content. It is considered an official standard of the Open Geospatial Consortium (OGC). The KML description can be used with many spatial components and purposes, e.g., with a Google Earth or Google Maps presentation [27], with a Marble representation [28], using OpenStreetMap (OSM) [29] and national instances.

The final result from the knowledge mining with the classified LX factual knowledge can be projected onto online satellite data of the area of the Kaali crater field. The result from object and sub-objects is shown in Figure 7.

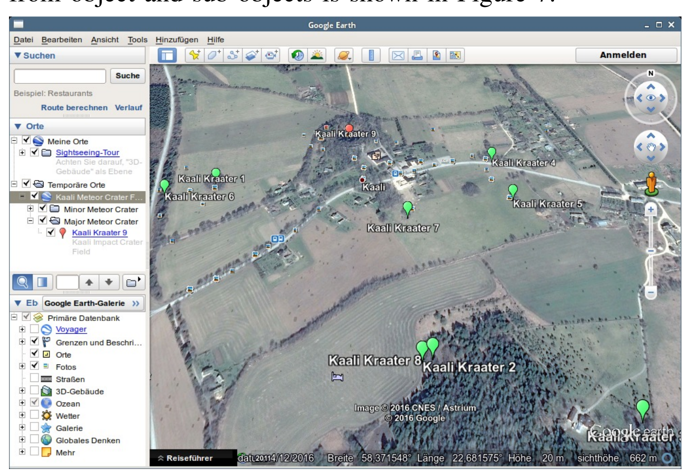

Figure 7. The resulting area of Kaali crater field, Saaremaa, Estonia, factual knowledge (craters red and green) (LX) projected onto Google Earth data.

The interactive map shows the nine craters known for the crater field. The major crater is marked in red colour, the minor craters are marked in green colour.

The the final result from the knowledge mining with the classified LX factual knowledge can be projected onto online vector and navigation data (Figure 8).

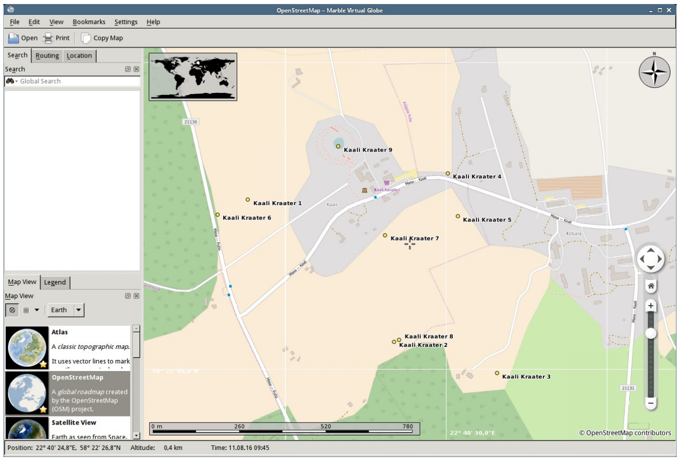

Figure 8. The resulting area of Kaali crater field, Saaremaa, Estonia, factual knowledge (craters 1 to 9) (LX) projected onto OSM data via Marble.

The integration shows craters 1 to 9 of the Kaali crater field area projected onto OSM data via Marble.

C. Resulting associated information: Media references

The integrated knowledge resources can contain references to any data, e.g., media objects. Media objects contain own references, e.g., classification, citations, documentation, and keywords and can therefore contribute in many ways to new insight – besides their intrinsic media content. The following photo data (Figure 9) from the media references for “Kaali crater” were delivered in association from the final result of the knowledge mining workflow.

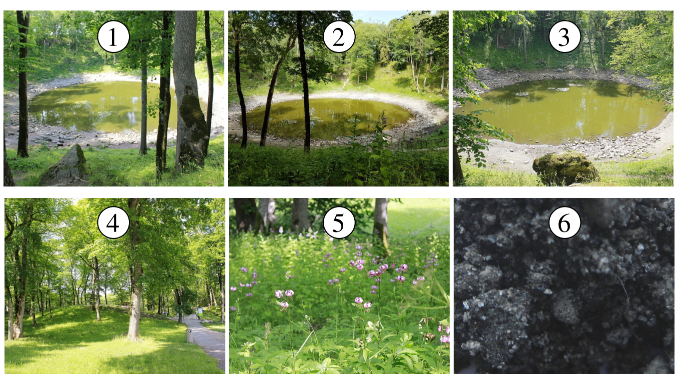

Figure 9. Integrated media photo objects associated with the knowledge object “Kaali crater”, Saaremaa, Estonia, referring to [30] (LX resources).

The references of these media photo objects (Figure 2) are part of objects in the knowledge resources. Media results (1–5) [30] and specimen (6) photos from the Natural Sciences Specimen Archive are dated June 29, 2016.

The photos and physical samples have been taken in 2016 by the Knowledge in Motion (KiM) natural sciences and archaeology sections at the Kaali meteorite crater field on the island of Saaremaa, Estonia, during the Geo Exploration and Information (GEXI) [31] Baltic research and studies campaign.

In detail, the resulting photo objects of the examined site (from left to right, from top to bottom) show in this sort order:

1: Major crater, view in northern direction.
2: Major crater, view in north-eastern direction.
3: Major crater, view in western direction.
4: Path towards major crater, view from southern direction.
5: Vegetation, Lilium martagon, at top of crater rim (referring to Figure 3).
6: Specimen crater pond material (quartz, melane particles, lacustrine deposits, biogenic material).

The references included in the knowledge mining workflow (Figure 4) provide the complementary information that fine particles from the Kaali crater include impactor remains (esp. significant Ni-Wüstite, Ni-Maghemite, Ni-Goethite, Hematite, Magnetite, Taenite, Kamacite), spherules and splash-forms.

V. Conclusion

This paper introduces a methodology for advanced knowledge mining, improving complex discovery and decision making results and providing potential for creating new insights.

A new practical knowledge mining procedure was successfully created based on the methodology. The mining procedure was used for efficiently integrating advanced knowledge resources and specialised application components for gaining new insight and cognition. The paper provides the results from the research and data-centric implementation of a case study of integrated knowledge and methods for answering knowledge mining challenges like complex questions. After the implementation, the case study concentrates on a context, which is derived from knowledge mining challenges associated with geosciences and archaeology. According to the methodology, the major phases were applied for the implementation. The paper presented the identification and mapping of required resources – knowledge resources and partial solutions, mapping of complementary components in their context, and excerpts of associated knowledge used for information peeling generating a base for the information processing. The resources provide conceptual and factual knowledge in integration with appropriate context data and application components for computing and visualisation.

The mapped application components – tools and filters – were used complementary for handling the complex resources, systematically peeling of information nuclei and facets, milling, and consecutive information processing, including decision making integrating spatial and conceptual criteria. The results of the knowledge mining information object turnaround, can itself become part of the knowledge resources. The methodology can be applied to many application scenarios, especially where a solution can only be gained by integration of different data and approaches. The various approaches also provide potential for optimisation for special priorities. In most cases, the optimisation can consider the individual challenges and the use of special algorithms and applications.

Future work concentrates on improving the multi-disciplinary knowledge resources and creating, utilising, and documenting advanced components for the knowledge mining cogwheel modules.

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