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Review

Linked Data Interfaces: A Survey

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Abstract: In the era of big data, linked data interfaces play a critical role in enabling access to and management of large-scale, heterogeneous datasets. This survey investigates forty-seven interfaces developed by the semantic web community in the context of the Web of Linked Data, displaying information about general topics and digital library contents. The interfaces are classified based on their interaction paradigm, the type of information they display, and the complexity reduction strategies they employ. The main purpose to be addressed is the possibility of categorizing a great number of available tools so that comparison among them becomes feasible and valuable. The analysis reveals that most interfaces use a hybrid interaction paradigm combining browsing, searching, and displaying information in lists or tables. Complexity reduction strategies, such as faceted search and summary visualization, are also identified. Emerging trends in linked data interface focus on user-centric design and advancements in semantic annotation methods, leveraging machine learning techniques for data enrichment and retrieval. Additionally, an interactive platform is provided to explore and compare data on the analyzed tools. Overall, there is no one-size-fits-all solution for developing linked data interfaces and tailoring the interaction paradigm and complexity reduction strategies to specific user needs is essential.

Keywords: linked data interfaces; semantic web; web of linked data; digital libraries; interaction paradigm

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1. Introduction

The landscape of Linked Data and the semantic web has extended its influence across diverse disciplines, revolutionizing how we handle and comprehend data. From academia to industry, from healthcare to entertainment, the principles of Linked Data and the semantic web have transcended traditional boundaries, offering a unifying framework for organizing and leveraging data. In light of this transformative impact, this review paper seeks to comprehensively examine the landscape of tools and interfaces developed within the context of Linked Data and the semantic web. We recognize that despite the remarkable advancements, there exists a need for a structured overview of the available tools, along with an exploration of their characteristics, functionalities, and evolving trends. By addressing these gaps, we aim to provide a valuable resource for researchers, practitioners, and enthusiasts navigating the intricate realm of Linked Data interfaces.

The primary objective of this review is to categorize and analyze a spectrum of Linked Data interfaces, elucidating their features and purposes. We delve into tools catering to semantic data management, traditional visual information seeking, semantic data visualization, collaborative annotation, and digital libraries. This comprehensive categorization allows us to pinpoint the strengths and limitations of existing tools and identify the emerging trends in the field. To accomplish this goal, we first identify five recurring macro-characteristics that encompass a diverse range of Linked Data interfaces:

Knowledge Extraction (2): Tools aimed at extracting knowledge from unstructured data.

Traditional Visual Information Seeking Tools (3): Conventional systems for seeking information through visual representations.

Visualization of Semantic Data (5): Tools for displaying retrieving and representing semantic data.

Semantic Annotation (5): Tools for collaboratively annotating semantic data.

Digital Library (6): Specific tools for the management and exploration of a collection of books.

In Figure 1, we present these macro-classification categories along with their respective sub-categories, offering readers a visual roadmap of the paper's structure. Subsequently, for each category, we conduct targeted searches to identify relevant tools, dissect their characteristics, and evaluate their impact. We then delve into dedicated sections where we describe and analyze the identified categories, presenting the representative tools that we consider instrumental within each classification.

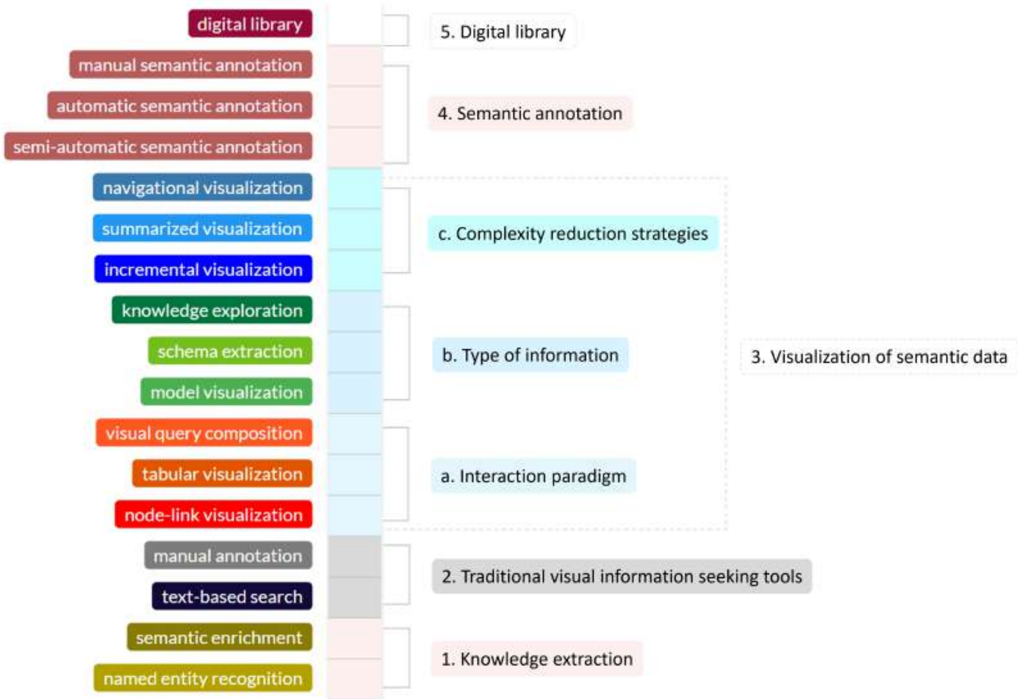

Figure 1. Classification categories.

In the following sections, we embark on this journey through Linked Data interfaces, exploring their functionalities, strengths, and areas for improvement. By uncovering the trends and patterns within these tools, we aim to contribute to a deeper understanding of the evolving landscape of Linked Data interfaces.

We select forty-seven tools that are most representative of their respective categories as a practical example. The tools are listed in Figures 2 and 3 with the categories to which they belong assigned.

While the research and literature provide us with a complete overview of methodologies, algorithms, and advantages, there exists a full list of domains of application that have taken advantage of the benefits of Linked Data Interfaces. Historically, one of the main uses of Linked Data was to support Natural Language Processing (NLP) tasks such as injecting ontologies or dictionaries into concepts expressed in natural language [1], expanding the knowledge of a domain by adding contextual information [2] or introducing explainability in recommendation tasks [3]. Closely related to natural language processing tasks, the field of Digital Libraries exploits the effectiveness and volume of Linked Data for tasks such as cataloguing, visualizing, and recommending resources [4]. Taking everything into account, we see opportunities for Linked Data Interfaces wherever there is a need to complete, integrate and connect (possibly heterogeneous) resources.

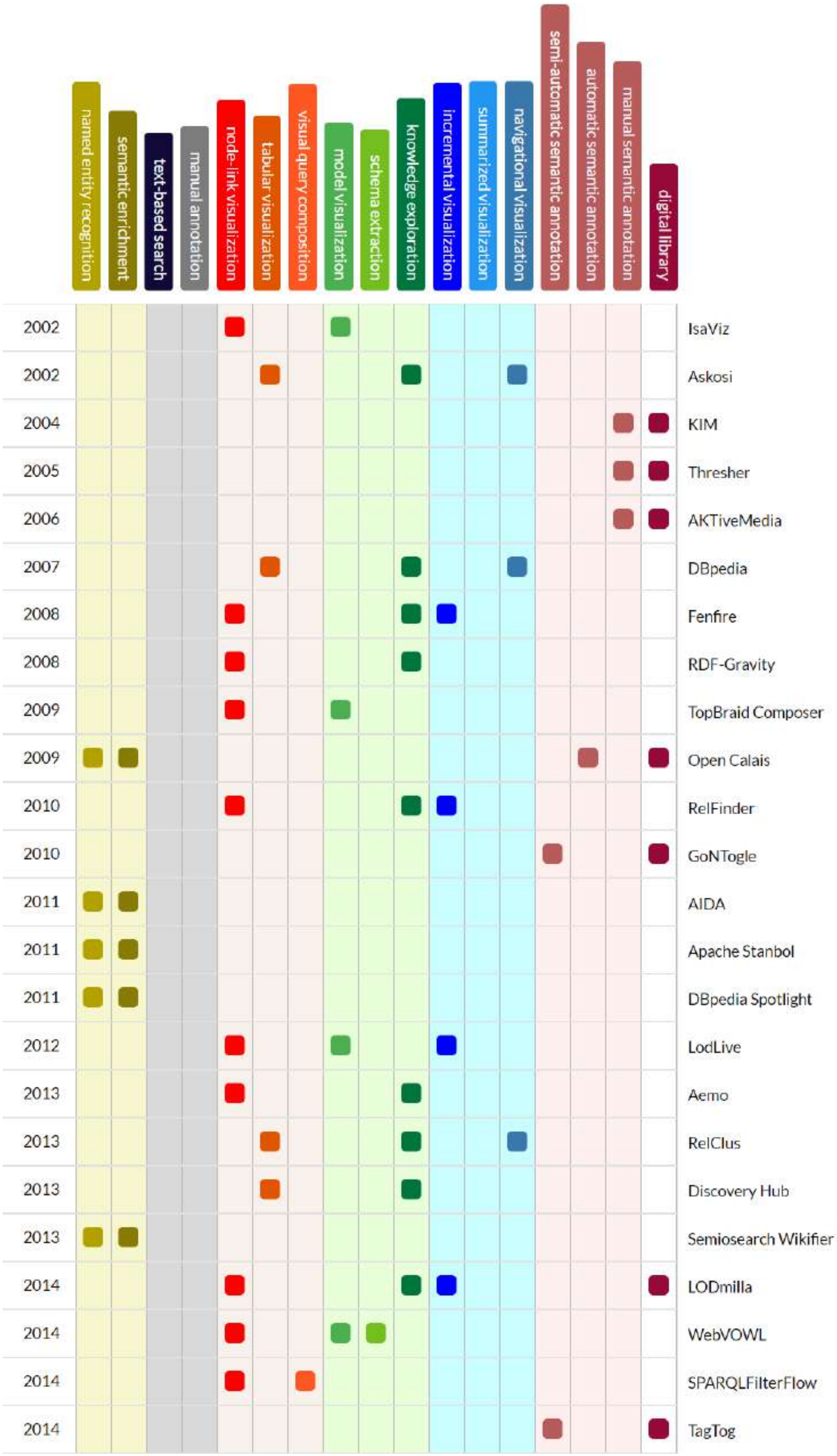

Figure 2. Semantic web tools-first part.

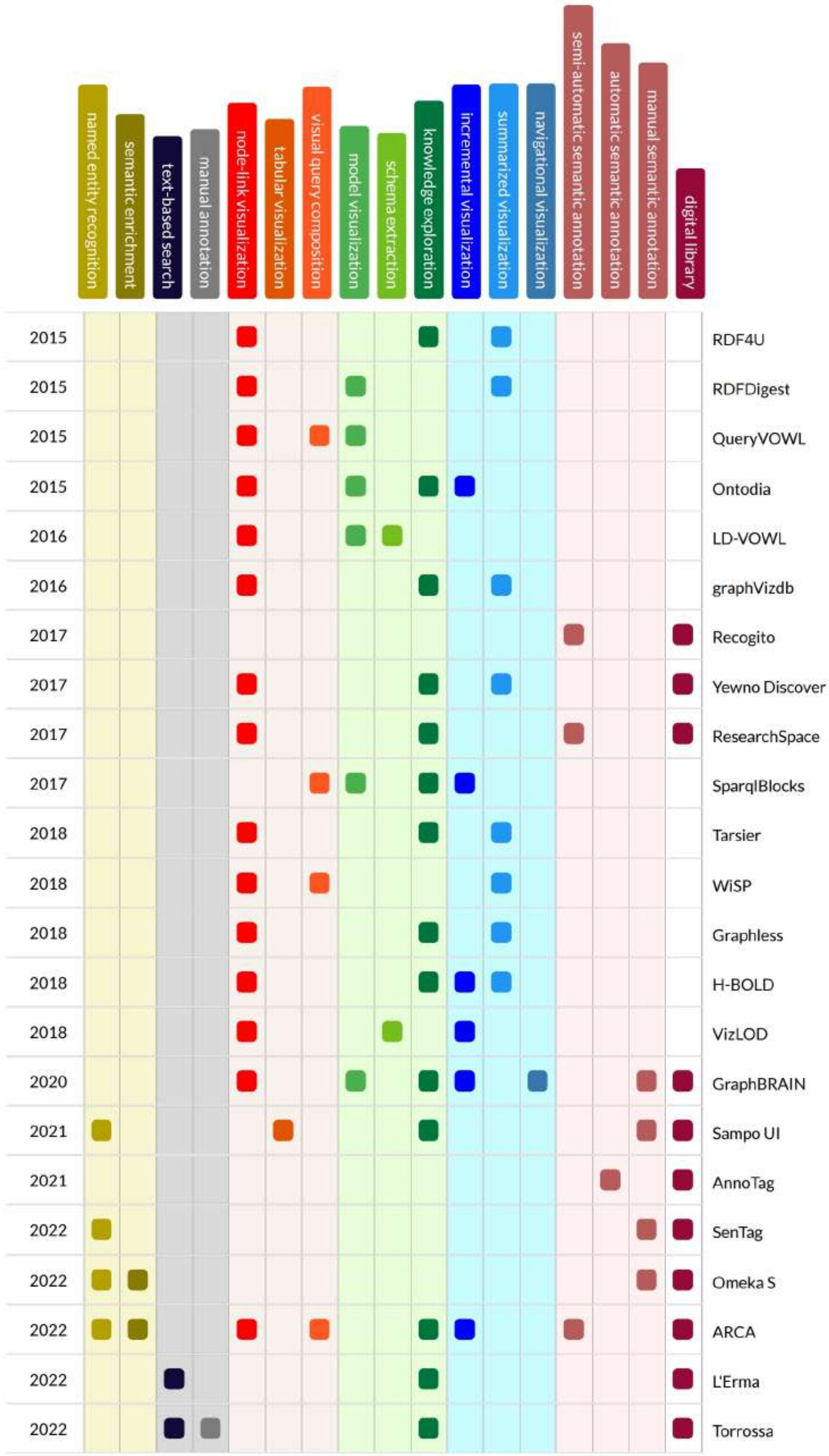

Figure 3. Semantic web tools-second part.

1.1. Survey Methodology

In conducting this survey, a systematic and comprehensive methodology was employed to ensure the thorough identification and analysis of Linked Data interfaces. The following steps outline the key steps taken in the methodology:

1. Literature Review and Search Strategy. We initiated the process with an extensive literature review to establish a foundational understanding of the landscape of Linked Data interfaces. This informed the development of a well-defined search strategy that included academic databases (Sapienza University of Rome: https://iris.uniroma1.it/, accessed on 26 July 2023; Aldo Moro University of Bari: https://ricerca.uniba.it/, accessed on 26 July 2023), online repositories (https://github.com/, accessed on 26 July 2023), and literature sources (Google Scholar: https://scholar.google.com/, accessed on 26 July 2023; Web of Science; Scopus). The search terms and keywords were thoughtfully selected to encompass the diverse spectrum of tools associated with Linked Data management, visualization, and exploration.

2. Tool Identification and Selection. Tools were systematically identified based on the defined search criteria. To ensure a comprehensive representation, multiple team members were involved in the tool identification process. Cross-referencing and iterative searches were conducted to minimize the possibility of overlooking relevant tools. Inclusion and exclusion criteria were applied to select tools that aligned with the scope of this survey.

3. Data Extraction and Categorization. For each identified tool, a detailed analysis was conducted to extract key features, functionalities, and characteristics. These data points were instrumental in categorizing tools into distinct macro-categories and sub-categories, reflecting the diverse functionalities offered by Linked Data interfaces.

4. Comparative Analysis and Trend Identification. Through a systematic approach, we analyzed the identified tools within each category, focusing on their strengths, limitations, and emerging trends. Comparative analysis aided in discerning patterns, while the identification of emerging trends provided insights into the evolving landscape of Linked Data interfaces.

5. Quality Assurance and Verification. To enhance the accuracy and reliability of our findings, a verification process was undertaken. The methodology, search strategy, tool identification, and categorization were reviewed by multiple team members to ensure consistency and minimize potential errors.

6. Transparency and Replicability. Transparency and replicability were paramount throughout the methodology. The systematic approach, search strategy, and selection criteria detailed in this paper provide readers with a clear understanding of our research process.

The employed methodology aimed to uphold objectivity, comprehensiveness, and rigor in capturing the breadth and depth of Linked Data interfaces. It facilitated the exploration of various categories of tools, their features, and emerging trends, ensuring that the resulting insights are both credible and valuable for our readers. Through the meticulous implementation of this methodology, we have endeavored to present a comprehensive and accurate overview of the landscape of Linked Data interfaces.

1.2. Outline of the Paper

In Section 2, we will describe the landscape of Knowledge Extraction tools. These tools are designed to extract knowledge from unstructured data sources, providing insights into their features, use cases, and limitations. Moving to Section 5, we delve into Traditional Visual Information Seeking Tools. This section will involve a comprehensive analysis of conventional systems used for retrieving information through visual representations. Through comparative analysis and case studies, we aim to assess the effectiveness and identify potential areas for improvement within these tools. Advancing to Section 3, our exploration centers on the Visualization of Semantic Data. We categorize these tools based on their interaction paradigms, discussing tabular and node-link visualization tools, as well as techniques for visual query composition. Additionally, we delve into the classification of these tools by the type of information they present, encompassing data visualization, model visualization, and schema extraction. In Section 5, we focus on the intricate domain of Semantic Annotations. Here, we delve into tools utilized for annotating semantic data, examining manual, automatic, and semi-automatic annotation techniques. Through a comparative evaluation, we provide insights into the diverse approaches aimed at enhancing data annotation. Transitioning to Section 6, we engage with tools specifically tailored for the Exploration of a Digital Library. These tools are crucial for managing and navigating collections of books within digital libraries. Our analysis encompasses user interfaces, innovative features, and the broader implications of these tools on enhancing the accessibility and exploration of digital content. Section 7 marks the culmination of our review, where we present the Conclusion and Emerging Trends. Here, we offer a concise summary of the paper's key findings, highlighting the diverse spectrum of Linked Data interfaces explored. Our discussion extends to the implications of our research and an identification of the emerging trends that provide insights into the future development of Linked Data and Semantic Web interfaces. Through this structured framework, our paper endeavors to provide a comprehensive exploration of the intricacies within Linked Data interfaces. Each section sheds light on specific tool categories, their functionalities, and their broader impact on the landscape of Linked Data and the Semantic Web.

2. Knowledge Extraction

Knowledge extraction is the process of transforming unstructured or semi-structured text into an output represented using a knowledge representation formalism. This process can be viewed as a specialized form of Information Extraction, with a heightened emphasis on employing advanced knowledge representation techniques to model and structure the extracted information. In the context of managing semantic data, the tasks of information extraction from unstructured sources and semantic enrichment hold paramount importance. These activities are essential for refining raw data into a more structured format that can be effectively utilized for various purposes. Several tools have been developed to facilitate these critical activities. These tools are designed to leverage cutting-edge techniques in natural language processing, machine learning, and knowledge representation to transform raw data into structured and machine-interpretable formats. By doing so, they enable the creation of coherent and organized knowledge representations that can be efficiently processed, queried, and reasoned upon. The significance of knowledge extraction and its role in converting unstructured data into valuable, structured insights is underscored by ongoing initiatives, such as the standardization of RDF extraction from relational databases. Furthermore, projects such as the conversion of Wikipedia into structured data, as seen in DBpedia and Freebase, exemplify how knowledge extraction contributes to enriching existing knowledge repositories. Below, we delve into a comprehensive exploration of tools and techniques employed for knowledge extraction, information enrichment, and their implications within the landscape of Linked Data interfaces.

AIDA [5] (Figure 4) is a framework and online tool used for named entity recognition (NER) and resolution. It takes a natural language text or a web table and maps mentions of ambiguous names to canonical entities (e.g., individual people or places) registered in the YAGO2 knowledge base. AIDA also provides sense tagging. The tool allows the algorithm's configuration with prior probability, keyphrase similarity, and coherence options. It is available as a demo web application or a Java RMI web service.

Apache Stanbol (https://stanbol.apache.org, accessed on 26 July 2023) is an Open Source HTTP service designed to assist Content Management System developers in semi-automatically enhancing unstructured content with semantic annotations to link documents with related entities and topics. The current enhancers include RDF encoding results from multilingual NER and resolution, sense tagging regarding DBpedia and GeoNames, text span grounding, confidence, and related images. It is available as a demo web application, REST service, or downloadable package.

DBpedia Spotlight [6] (Figure 5) is a tool for automatically annotating mentions of DBpedia resources in text. It is available as a demo web application, REST service, or downloadable package.

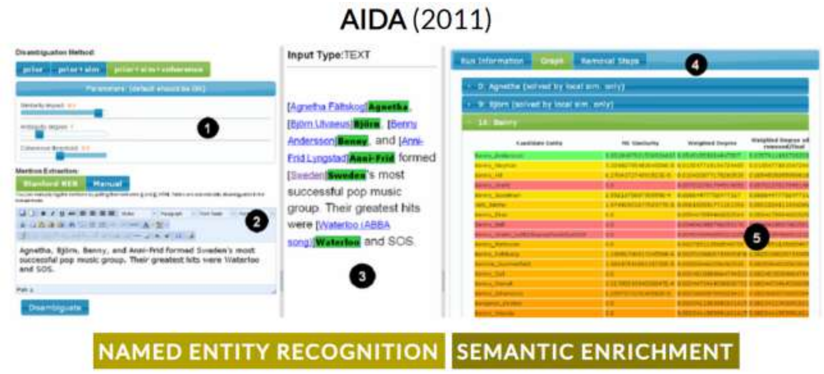

Figure 4. AIDA.

Figure 5. DBpedia Spotlight.

Open Calais [7] (Figure 6) is a Knowledge Extraction tool that extracts named entities with sense tags, facts, and events. It is available as a web application and as a web service. The tool has been used via the web application for consistency with other tools. The Open Calais TopBraid Composer plugin can automatically produce an RDF file. However, the RDF schemata used by Open Calais have mixed semantics and need to be refactored to conform to a standard output relevant to the domain addressed by the text.

Semiosearch Wikifier [8] (Figure 7) resolves arbitrary named entities or terms (i.e., individuals or concepts) to DBpedia entities by integrating several components: a named entity recognizer, a semiotically informed index of Wikipedia pages, and matching and heuristic strategies. It is available as a demo web application.

There has been much recent research on how to attach semantics to unstructured data [9], through processes such as Named Entity Recognition and Linking (NERL).

The **GLOBDEF system** [10,11] works with pluggable enhancement modules, which can be dynamically activated to create on-the-fly pipelines for data enhancement.

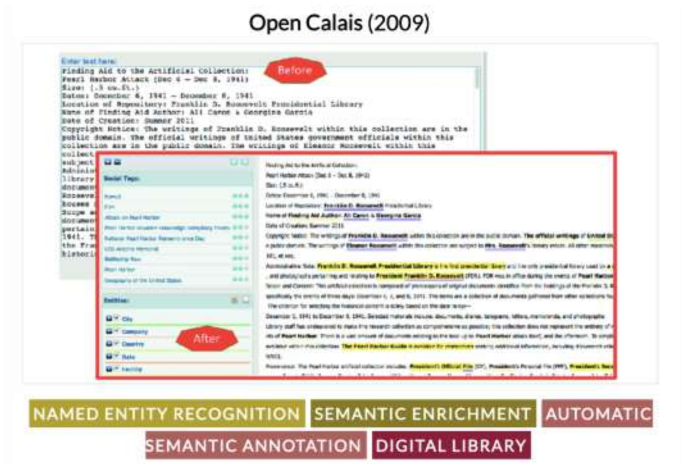

Figure 6. Open Calais.

Figure 7. Semiosearch Wikifier.

Both tools provide interesting paradigms to build a flexible pipeline for semantic enrichment. In conclusion, Knowledge Extraction has witnessed significant advancements in developing sophisticated tools and frameworks. These tools aim to bridge the gap between unstructured or semi-structured textual data and structured knowledge representations. Critical trends in these tools include Named Entity Recognition and Linking (NERL) for identifying and disambiguating entities, semantic enrichment to add valuable annotations, and multilingual support for broader applicability.

The tools described in this section, such as AIDA, Apache Stanbol, DBpedia Spotlight, Open Calais, and Semiosearch Wikifier, offer diverse functionalities and capabilities. They utilize existing knowledge bases to enhance accuracy and provide configurability options to suit specific use cases. Additionally, some tools facilitate seamless integration through web services and APIs.

One important direction is the increasing focus on information retrieval, with efforts to incorporate semantic information into retrieval systems and user-friendly front-ends. Active learning techniques are also emerging to improve extraction performance continuously. However, it is crucial to consider the maintainability and upkeep of these tools, as some of them face challenges in terms of maintenance and updates, as seen with GLOBDEF and Stanbol.

These knowledge extraction tools play a vital role in managing semantic data, enabling better understanding and utilization of unstructured information. As the field continues to evolve, we can expect even more innovative solutions to emerge, catering to the diverse needs of knowledge extraction and utilization across various domains and applications.

3. Traditional Visual Information Seeking Tools

Traditional Visual Information Seeking Tools are systems that rely on conventional search methodologies without the incorporation of semantic technologies. These tools are designed to assist users in retrieving and comprehending information through visual representations. In the analysis of these tools, we examine their approaches to information representation, exploring how they present data visually to users. This investigation serves as a basis for comparison with tools that specialize in visualizing semantic information. By contrasting the information presentation strategies of traditional tools with those of semantic visualization tools, we gain insights into the strengths and limitations of each approach and their applicability within the Linked Data interface landscape. The literature on visual information seeking has made significant contributions [12–14]. Early attempts to create visual search interfaces date back to the early 1990s [15], where researchers applied direct manipulation principles to search interfaces, leading to the development of dynamic queries [16].

Dynamic queries are visual query systems, often based on the query-by-example paradigm [17], allowing users to manipulate sliders and graphical controls to modify search parameters. The system immediately presents the results of these changes in a visualization to users.

As an example of a traditional digital library search system, the site of the publishing house **L'Erma di Bretschneider** (http://www.lerma.it, accessed on 26 July 2023) (Figure 8) features a search tool called *Lerma*. It allows users to search for books based on keywords contained in book titles and specific categories.

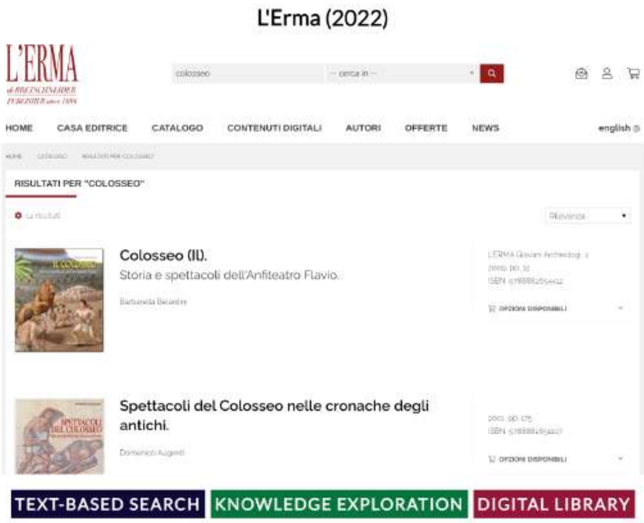

Figure 8. L'Erma di Bretschneider.

Similarly, **Torrossa** (https://www.torrossa.com, accessed on 26 July 2023) is the digital search platform of "Casalini Libri," with content contributed by approximately 180 publishers, mainly from Italy and Spain. Torrossa enables advanced searches based on metadata and words contained in the books.

However, a limitation of these systems, especially when dealing with unstructured information such as books, is that exploring and filtering by basic metadata (e.g., author, title) can be useful but often proves insufficient.

To overcome these limitations, the use of semantic entities assigned to documents enhances traditional keyword-based search by providing:

1. Proper Semantic Facetted Browsing: This enables users to filter search results based on relevant semantic facets, providing a more refined and meaningful search experience.
2. Extension of Query String with Related Entities and Keywords: Users can explore more comprehensive and relevant search results by incorporating related entities and keywords into the search query.

3. Recommendations and Cross-connections: Utilizing semantic relationships, the system can recommend related documents and provide further search suggestions based on cross-connections between entities.

By incorporating semantic capabilities, these information-seeking tools significantly improve the effectiveness and efficiency of search processes, facilitating a more intuitive and insightful exploration of information.

4. Visualization of Semantic Data

The extracted semantics from a corpus of documents (Section 2) can be incredibly valuable for exploration, but they differ from fixed and homogeneous sets of predefined metadata. Therefore, data models and visual user interfaces must be designed to handle these complex and heterogeneous data.

Efforts in the field of semantic web [18] and LD [19] focus on data modeling, integration, and interaction for this type of data on the web. These endeavors have contributed to the emergence of Knowledge Graphs (KGs), which are used to organize complex datasets by integrating multiple sources [20,21].

Numerous user interfaces for visualizing and exploring KGs exist, and new ones continue to be developed, mainly using semantic web and LD technologies [22–25].

The visualization and exploration of KGs play a crucial role in making sense of intricate relationships and interconnectedness within data. These interfaces provide powerful tools for users to navigate, analyze, and comprehend the underlying semantic structures, leading to better insights and decision-making in various domains. As the field advances, we can expect even more sophisticated and innovative approaches to further enhance the visualization and exploration of semantic data.

4.1. By Interaction Paradigm

Numerous tools have been created to provide simple interactive functionalities, enabling users to visually delve into Knowledge Graphs (KGs) sourced from data files or SPARQL endpoints.

This section classifies LD viewing tools based on their interaction paradigms. An interaction paradigm pertains to the approaches and procedures employed by tools to generate a visual depiction of data that can be directly explored and analyzed within the visualization itself. Various interaction paradigms facilitate diverse data-driven insight methodologies.

We have recognized three distinct types of interaction paradigms:

Tabular: Interfaces with a tabular interaction paradigm display information about a single resource in one visualization. Views focus on tables that show specific properties linked to the asset, such as media files (e.g., photos), descriptions, or links to other linked assets.

Node-link: In the node-link paradigm, resources are represented by nodes or boxes, while triples are represented by arcs that connect the resources. The graph can be explored by moving from one resource to another using the relative arcs. The node-link view can be static or dynamic, with the latter allowing for interaction.

Visual Query Composition: The visual query paradigm encompasses user interfaces that empower users to execute sophisticated queries without requiring expertise in the RDF model or the SPARQL language.

Each provides a unique approach to visualizing and exploring LD, catering to user preferences and requirements. Users can gain valuable insights and knowledge from the KG by understanding and leveraging these paradigms.

4.1.1. Tabular Visualization Tools

DBpedia (https://www.dbpedia.org, accessed on 26 July 2023) (Figure 9) is a project with the objective of extracting structured information from Wikipedia content. DBpedia built in interface presents data in a tabular form, represented as a list of triples. On the resource page, users can explore all connections (triples) where the resource serves as a subject or object, encompassing both inbound and outbound relationships.

The user's interaction with this interface allows them to click on predicates and objects, which are represented as links (written in blue and underlined). Clicking on these links enables users to jump from one page to another, exploring related resources. Every resource within DBpedia is interconnected through these links, facilitating exploration and navigation of the vast web of LD.

Figure 9. DBpedia.

The tabular visualization offers an intuitive and straightforward way to interact with the LD, empowering users to traverse through interconnected resources and gain deeper insights into the relationships and connections within the knowledge graph.

4.1.2. Node-Link Visualization Tools

Aemoo [26] (Figure 10) aims to extend the information available in a SPARQL endpoint by enabling exploratory search across the web. The tool collects data from the DBPedia endpoint and enhances it with information from Wikipedia, Google News, and Twitter. Its primary objective is to bridge the gap between the Semantic Web and the traditional Web, providing comprehensive insights about a resource. Aemoo primarily relies on Wikipedia as its main information source. It gathers all Wikilinks associated with a resource and organizes them into "set nodes," each containing resources of the same class. Furthermore, Aemoo explores Google News and Twitter to obtain additional information related to the subject. The resulting graph displays all set nodes, with the core node representing the resource of interest. Hovering over an entity reveals contextual information about the relationship between the subject and the hovered element, often extracted from Wikipedia. Aemoo's approach is grounded in knowledge patterns, which capture essential elements contributing to knowledge about specific events.

LODmilla [27,28] (Figure 11) offers link-node navigation, empowering users to search and uncover hidden data associations within the Linked Data (LD) using nodes. Rather than directly displaying the underlying data, LODmilla's interface facilitates exploration and analysis by enabling users to traverse the Knowledge Graph through nodes.

Tarsier [29] (Figure 12) offers an interactive 3D graph visualization of LD sources. The tool utilizes the metaphor of semantic planes, where each plane groups elements that share a common concept, such as elements belonging to the same class or sharing the same property. Users can create and split semantic planes through user interface commands, and the 3D environment allows for personalized layout adjustments, enabling users to move elements between different planes and gain different perspectives by rotating the graph. Resources are represented as spheres placed over concentric circumferences, with classes typically located over smaller circumferences and instances over wider ones. Tarsier employs a visual schema to differentiate heterogeneous elements that are not explicitly labeled, requiring users to click on nodes or edges to understand their representations. The tool allows for the creation of graphs after the insertion of a SPARQL query, but they are not expandable, limiting exploratory searches.

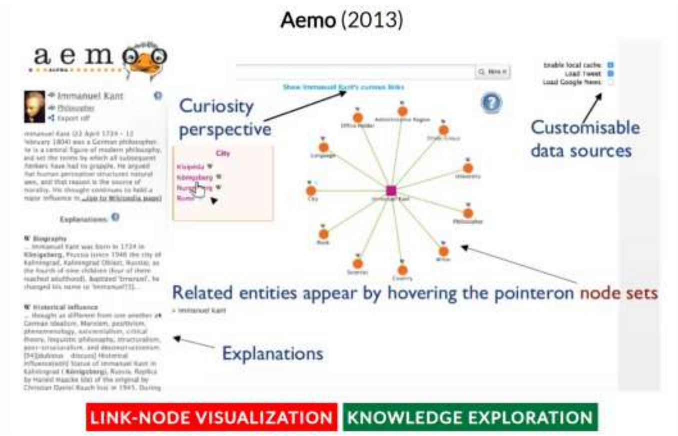

Figure 10. Aemoo.

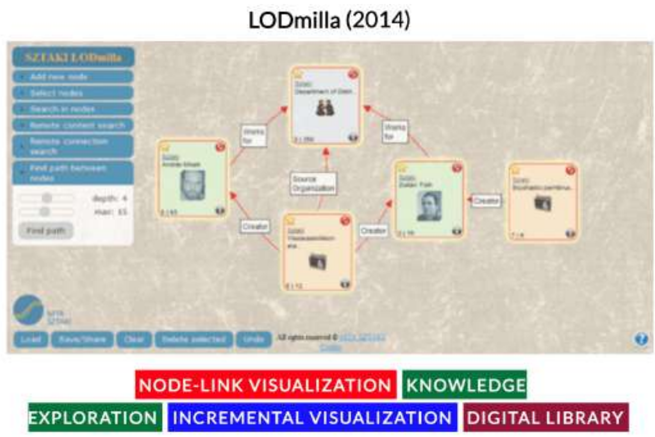

Figure 11. LODmilla.

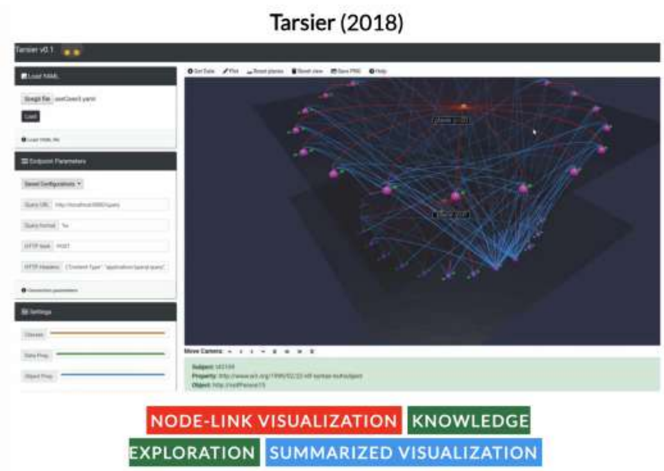

Figure 12. Tarsier.

Node-link visualization tools such as Aemoo, LODmilla, and Tarsier provide valuable means to explore and comprehend the complex relationships and connections within KGs.

Each tool employs distinctive approaches and functionalities to support users in gaining insights from the interconnected web of semantic information.

4.1.3. Visual Query Composition

In another context, certain tools employ node-link visualizations to tackle the issue of visual query composition. These tools empower users without prior knowledge of Semantic Web technologies to articulate SPARQL queries through intuitive graphical representations.

One such tool is **SPARQLFilterFlow** [30] (Figure 13), a web-based application built on a filter/flow model. It allows users to formulate SPARQL queries using graphical elements presented in a tree-based visualization. By arranging and connecting these graphical elements, users can effortlessly construct complex SPARQL queries.

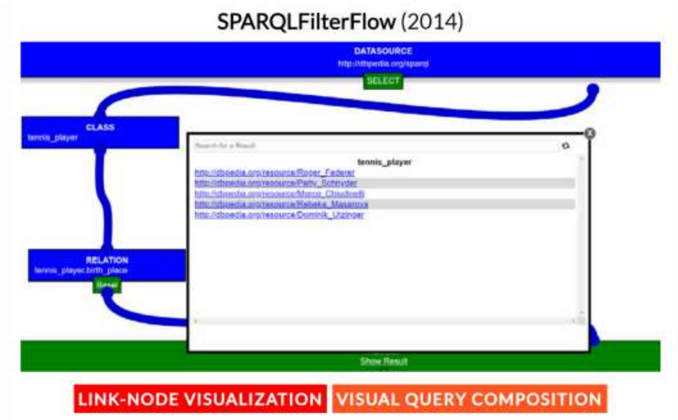

Figure 13. SPARQLFilterFlow.

Likewise, **QueryVOWL** [31,32] (Figure 14) employs visual elements inspired by VOWL graphical representations to create graphs, which are subsequently automatically transformed into SPARQL queries. The main emphasis of this tool lies in query construction rather than data exploration.

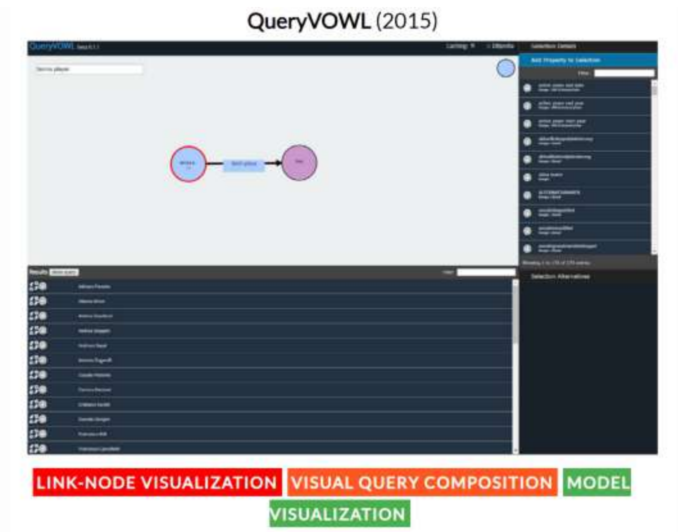

Figure 14. QueryVOWL.

RDF Explorer [33] offers an interface similar to QueryVOWL, but where the user starts from the data, rather than the model. The node-link paradigm for exploration is paired with a mechanism to build queries by replacing nodes with variables. The results of a query may be used to refine the query itself or further explore the dataset.

SPARQlBlocks [34,35], while still amenable to non technical users, offers a view of queries that more closely resembles the SPARQL structure. It is based on the block paradigm, where the user is free to create and modify queries using basic building blocks. As in RDF Explorer, the results of a query can be directly used to change/refine the query or create new queries. By using the metaphor of blocks for multiple queries and results in the same coherent workspace, it aims to support modular query design while guiding the user through a proven interaction model.

Finally, some SPARQL query builders, such as the **Wikidata Query Builder** or **Sparnatural** [36], are fundamentally form-based. They are nevertheless still considered query builders because the user can extend and modify the query conditions expressed by the available form to design relatively complex queries. They do not give the users the same flexibility of the previous approaches, offering in exchange user interfaces that may be easier to learn by a lay user.

These visual query composition tools significantly lower the barrier of entry for users who may not be familiar with SPARQL and Semantic Web technologies. By providing an intuitive and visual approach to query formulation, these tools facilitate a more user-friendly interaction with LD sources, making it easier for users to retrieve relevant information from complex knowledge graphs.

4.2. By Type of Information

In this subsection, we categorize tools based on the type of information they represent. The classification includes the following:

Data Visualization: These tools are designed to visualize the actual data, presenting it in various graphical formats for better understanding and analysis.

Model Visualization: Tools falling under this category display data models, including schemas and ontologies, providing users with an overview of the underlying structure of the data.

Data to Model Visualization: The tools in this category start with the raw data and then extract and visualize the underlying data model, revealing the relationships and connections within the data.

The following descriptions provide an overview of the tools within each category.

4.2.1. Data Visualization

Knowledge exploration tools constitute a distinct category of information retrieval, allowing users to uncover related information within various knowledge bases and discover relevant content. Unlike targeted searches with predefined goals, knowledge exploration involves open-ended exploration, where users engage in learning, exploration, and evaluation activities to gain insights and discover new information.

Discovery Hub [37] (Figure 15) stands as an advanced tool for knowledge presentation and exploration. It shares similarities with QueryVOWL but focuses exclusively on knowledge derived from DBpedia. The tool offers an interactive and visually rich environment to explore and analyze data from DBpedia, empowering users to navigate the KG and uncover valuable insights.

In data visualization, tools like Discovery Hub are pivotal in facilitating knowledge discovery, enabling users to interactively explore vast knowledge bases and discover connections and patterns within the data.

4.2.2. Model Visualization

Tools in this category are dedicated to the visualization of data models, including schemas and ontologies, offering users insights into the underlying structure and relationships within the data.

GraphBRAIN [38,39] is a versatile tool designed for the creation and collaborative development of KGs based on the Labeled Property Graph (LPG) model, offering advanced solutions for their exploration, consultation, and analysis. It also provides web services that other applications can utilize. One of the unique aspects of GraphBRAIN is its integration of methods and tools from various research domains.

Ontodia [40] (Figure 16) is a web-based tool designed for visualizing ontologies and semantic datasets, with additional features for sharing and distributing resulting diagrams. It adopts a 2D node-link visualization approach, incorporating a UML-inspired method to display additional information about nodes.

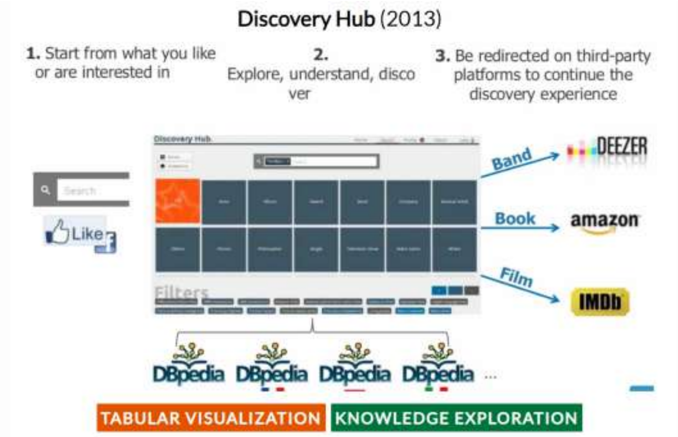

Figure 15. Discovery Hub.

Regarding layouts, Ontodia offers force-directed and grid layouts. It includes a hierarchical relationships view that presents parent-child relationships between classes in a tree layout. The tool allows users to drag and drop instances onto the diagram, giving them the flexibility to adjust the view by rearranging items, removing nodes, and toggling links between nodes.

Ontodia facilitates data exploration, enabling users to sort nodes related to a selected node. By dragging and dropping related nodes from the instance panel onto the canvas, users can expand the graph and explore the ontology further.

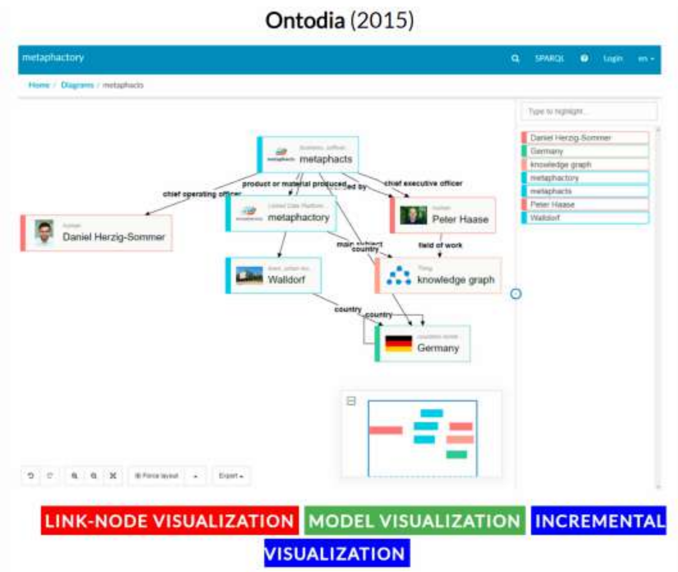

Figure 16. Ontodia.

A notable feature of Ontodia is its diagram management capabilities. Users can publish the fixed URL of a diagram on the web, share it with others via email, or lock it for personal use. The tool introduces the concept of data source entities, and access to these can be managed similarly to controlling access to a diagram. Searching and filtering options are available for classes, instances, and links.

It is worth mentioning that Ontodia was designed to simplify ontology and semantic data visualization. As such, some OWL constructs were omitted, retaining only the basic ones on the graph.

TopBraid Composer (https://www.w3.org/wiki/TopBraid, accessed on 26 July 2023) (Figure 17) is primarily designed for ontology editing but also offers visualization as a side feature. The visualization method is UML-inspired, with a horizontal or vertical tree layout, along with a classic indented list view. Classes and properties are depicted as nodes connected with oriented edges labeled with their respective predicate names. The visualization is conducted at the RDF level, even representing owl:Class as a separate node, and each class is connected to it through an rdf:type edge.

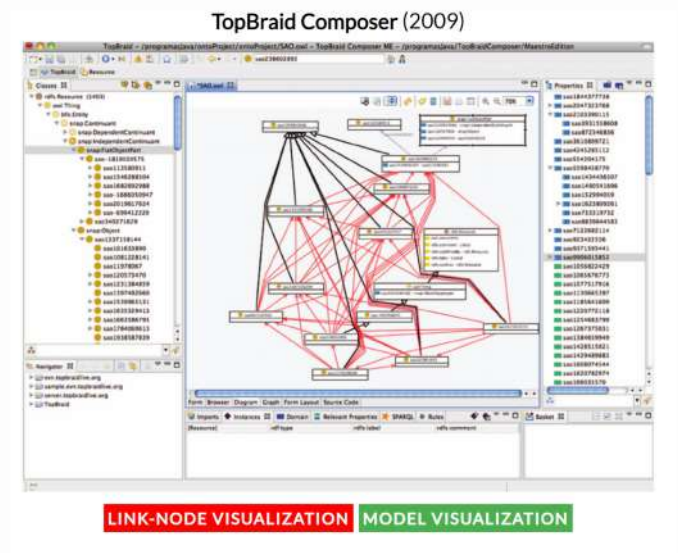

Figure 17. TopBraid Composer.

WebVOWL [41] (Figure 18) is a web-based application dedicated to providing user-oriented visualizations of ontologies. It utilizes the Visual Notation for OWL Ontologies (VOWL) to create graphical representations of OWL elements, organized in a force-directed graph layout. The tool allows users to interact with the ontology visualization, enabling exploration and customization. The VOWL visualizations in WebVOWL are automatically generated from JSON files. To achieve this, ontologies need to be converted to the JSON format using the provided Java-based OWL2VOWL converter. The force-directed graph layout relies on a physics simulation, resulting in dynamic animation that adjusts node positions dynamically. WebVOWL strictly adheres to the VOWL specification when rendering graphical elements, ensuring consistent and standardized visualizations.

4.2.3. Data to Model Visualization (Schema Extraction)

In the context of Linked Data (LD), the problem of data to model visualization, also known as schema extraction, has gained attention. Several tools have emerged to address this challenge and infer ontology schema from RDF triples using SPARQL queries.

VizLOD [42], LD-VOWL [43] (Figure 19), and RDF2Graph [44] are examples of such tools that leverage SPARQL queries to process RDF triples and extract schema information. These tools focus on inferring the ontology schema from the LD and presenting the most representative concepts. They employ various methods and assumptions, such as considering classes with a significant number of instances as representative. The extracted ontology schema is then progressively visualized as a graph, offering various interactive operations for exploration and analysis.

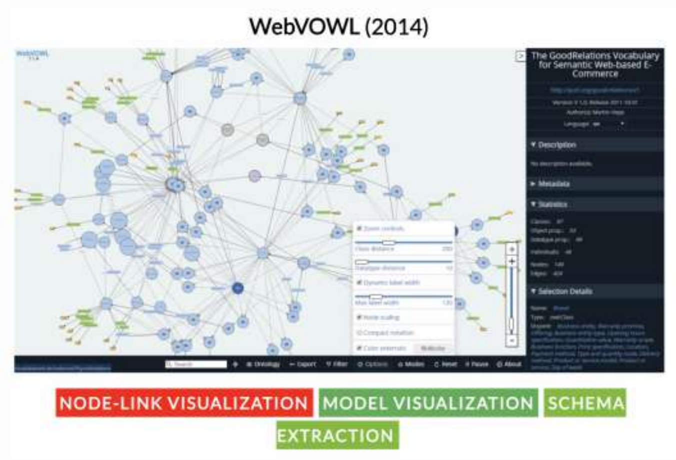

Figure 18. WebVOWL.

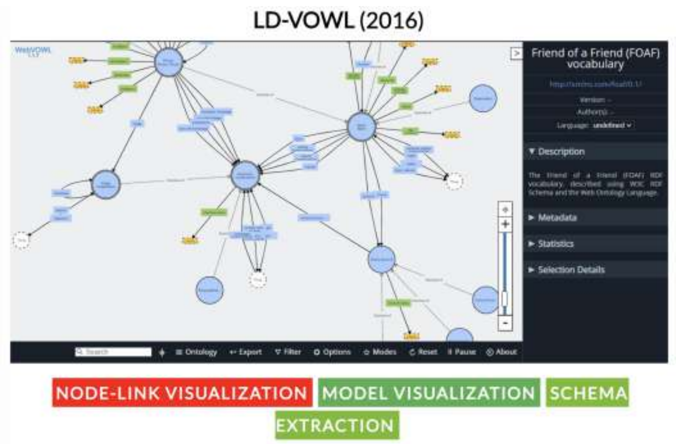

Figure 19. LD-VOWL.

4.3. Complexity Reduction Strategies

Visualizing a large number of data objects can be challenging and often leads to information overload. To address this issue, modern systems employ complexity reduction strategies to effectively support data reduction and abstraction.

Three main strategies for reducing the displayed information have been identified:

- **Navigational visualization**. This strategy centers around a particular data object, typically a resource, and facilitates exploration of its immediate surroundings or "neighborhood". Users can navigate to directly related resources, making it a common choice in tabular interaction paradigms.
- **Incremental visualization**: The incremental visualization paradigm is often employed in dynamic node-link user interfaces. Users have control over a workspace where they can add or remove views of specific data objects from the dataset as needed. Shortcuts are often available to visualize data objects related to the ones already in view.
- **Summarized Visualization**: Some tools use data reduction techniques to generate graph summaries, providing an overview of a dataset while avoiding the issue of overplotting in large graph visualizations.

Below are described some tools that belong to each listed category.

4.3.1. Navigational Visualization

Moving away from the paradigm of simple linear search result lists, modern navigation features such as node-link views, cluster maps, geographic maps, and timelines offer more expressive ways for users to perceive information. Given the high diversity of relationships between entities, interfaces must be highly versatile. This necessitates methods for visually structuring information based on the user's interests, thus assigning specific relevance to related entities.

For instance, when viewing information about the DBpedia entity "Imperatore Augusto", there are over 600 facts (RDF triples) available. Displaying such a vast amount of information at once would overwhelm the user, and each user may have different preferences. To address this, heuristics based on statistical and semantic analysis of the underlying RDF graph structure are employed to classify related entities based on their relevance. As a result, relevance rankings are tailored to individual users.

User behavior can be monitored through log file analysis, enabling the generation of user profiles that can be mapped to specific LOD sub-charts representing the user's interests. This way, the user experience can be further customized and personalized.

This enables:

- Customized relevance ranking based on individual preferences.
- Personalized search recommendations tailored to each user.

4.3.2. Incremental Visualization

There are several Web exploratory tools designed for incremental visualization, offering interactive graph-based browsing of LD. These tools enable users to dynamically expand their exploration by following links starting from a given URI or SPARQL endpoint. Notable examples include **Fenfire** [45] (Figure 20), **LodLive** [46] (Figure 21), and **LodView** (https://lodview.it, accessed on 26 July 2023).

Fenfire (Figure 20) is a powerful tool that allows users to progressively build and explore visualizations of Linked Data. It offers an interactive graph-based interface where users can add new elements, remove existing ones, and modify the layout as needed. The incremental nature of Fenfire's visualization lets users control their workspace and dynamically adjust the data objects in view. Additionally, shortcuts are provided to visualize data objects related to those already displayed.

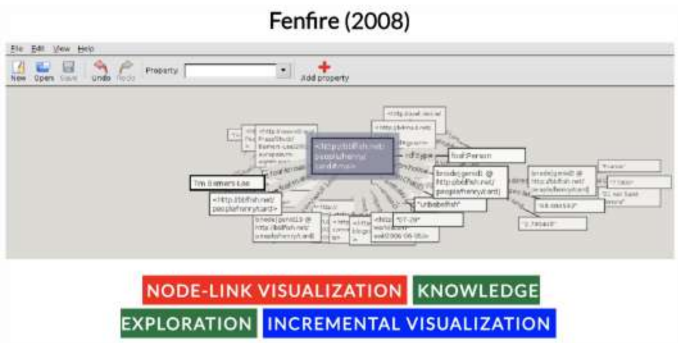

Figure 20. Fenfire.

LodLive is another LD visualization tool that offers an incremental exploration experience. Users can start their exploration from a single resource and then expand their search by exploring the properties of connected elements displayed on the screen. This tool supports multiple endpoints, enabling retrieval of information from various sources based on the URI provided by the user. The visualization presents resources as circles, with the value of the property rdfs:label displayed within. Smaller concentric circles represent objects connected to the central resource, and clicking on these circles allows further expansion. LodLive emphasizes inverse properties, owl:sameAs relations, images, and geographic data, presenting them in distinct ways to aid the user's understanding. It also enables users to gather information from different endpoints related to resources linked through the owl:sameAs property.

Both Fenfire and LodLive facilitate an iterative exploration process, empowering users to incrementally build their understanding of complex datasets while providing interactive and dynamic graph-based visualizations for effective data analysis and comprehension.

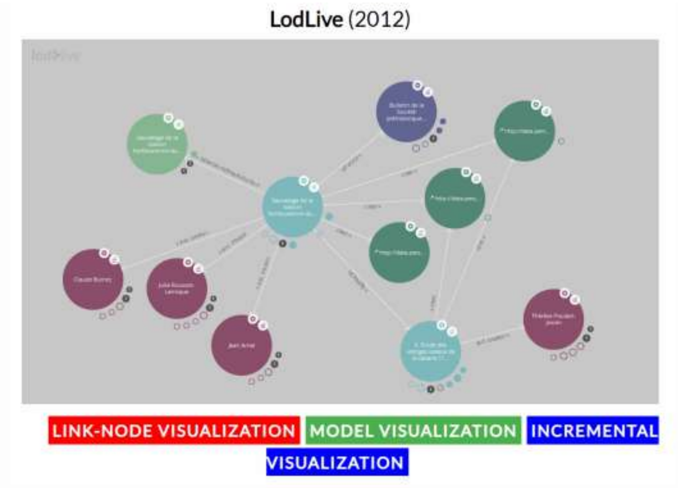

Figure 21. LodLive.

4.3.3. Summarized Visualization

In the realm of summarized visualization, several tools have been developed to provide users with an abstracted and concise overview of large Linked Open Data (LOD) datasets, allowing them to explore significant sources without the need for deep knowledge of SPARQL or dataset content. These tools recognize the inherent complexity of LOD, which can encompass vast interconnections and a multitude of data points. As such, they serve as indispensable aids for both novice and expert users alike, presenting a simplified and coherent representation of the data landscape. These summarized visualization tools deploy various strategies to distill intricate LOD datasets into digestible forms. Through techniques such as aggregation, filtering, and clustering, they condense the information while preserving the essence of meaningful relationships and patterns. By presenting high-level insights at a glance, users can promptly identify key entities, trends, and connections without being overwhelmed by the dataset's sheer volume. One of the key advantages of these tools is their accessibility. Users can engage with LOD datasets without grappling with the complexities of constructing intricate SPARQL queries or understanding the underlying ontology structures. This democratization of LOD exploration aligns with the broader goal of making linked data more approachable to a wider audience, fostering collaborative exploration and discovery. Furthermore, the utility of summarized visualization tools extends beyond data exploration. Researchers, analysts, and decision-makers can swiftly extract valuable insights from LOD datasets for informed decision-making, trend analysis, and hypothesis generation. This facilitates a seamless transition from data to actionable knowledge, accelerating the process of deriving meaningful value from interconnected datasets. Below, we delve deeper into the workings of summarized visualization tools, dissecting their methodologies and examining their effectiveness in conveying meaningful insights from LOD datasets. Through detailed case studies and comparative analyses, we aim to illuminate the strengths, limitations, and potential innovations within this critical aspect of Linked Data interfaces.

H-BOLD (High-level visualization over Big Linked Open Data) [47] (Figure 22) is an evolution of LODeX and addresses the challenge of presenting complex datasets in a visually interpretable manner. It employs an incremental multilevel exploration approach, utilizing a community detection algorithm to construct abstract levels effectively. The tool aggregates classes into clusters, enabling summarized visualization of the dataset. Users can incrementally explore classes as needed, with the option to expand the abstract representations on-the-fly for more detailed visualization. H-BOLD generates a "Schema

Summary" by collecting essential information (e.g., number of triples, class list, property list, and class relations) about datasets in a data store. For large datasets, the community detection algorithm creates a "Cluster Schema", reducing visual clutter and enhancing comprehension. This tool provides a fast and compact overview of SPARQL endpoint content, facilitating efficient exploration and comprehension.

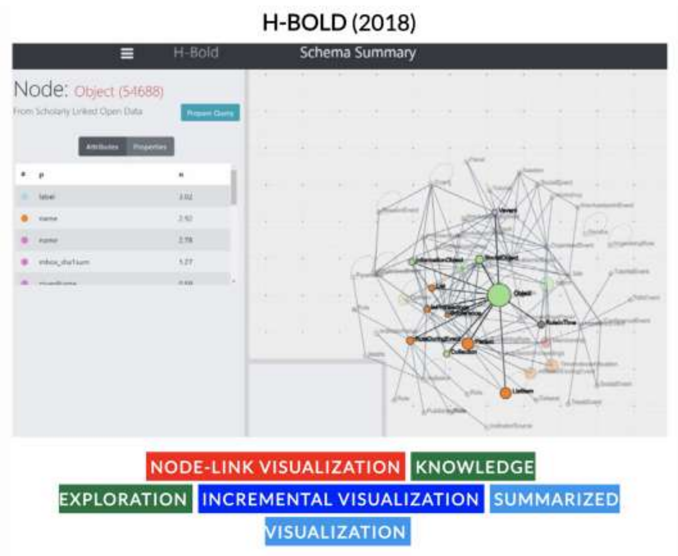

Figure 22. H-BOLD.

RDF4U [48] (Figure 23) is another tool that offers graph visualization over summarized graphs. It combines graph simplification, triple ranking, and property selection to present relevant information effectively. The tool automatically analyzes data collected from queries and identifies redundant information during graph simplification. It handles equivalent, transitive, and hierarchical classification relations, merging "owl:sameAs" nodes and focusing on displaying common information initially. Users can interactively add topic-specific information to the graph as needed. The user interface is minimal, allowing users to concentrate on the visualization. RDF4U is adaptive for different users, catering to both non-technical users and domain experts. General users can focus on general information while hiding domain-specific details, while domain experts can easily visualize specific information by hiding the general parts.

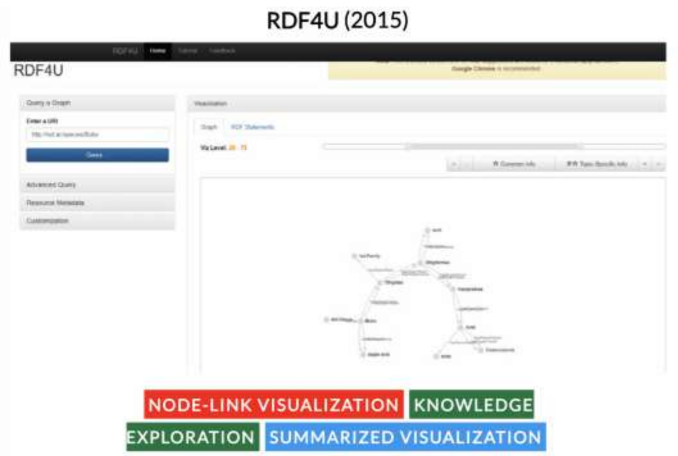

Figure 23. RDF4U.

Graphless [49] (Figure 24) is a visualization tool that generates summaries based on statistical data, such as nodes' connectivity degree and property frequency. The tool abstracts the dataset to highlight relevant patterns and key insights without overwhelming users with excessive detail.

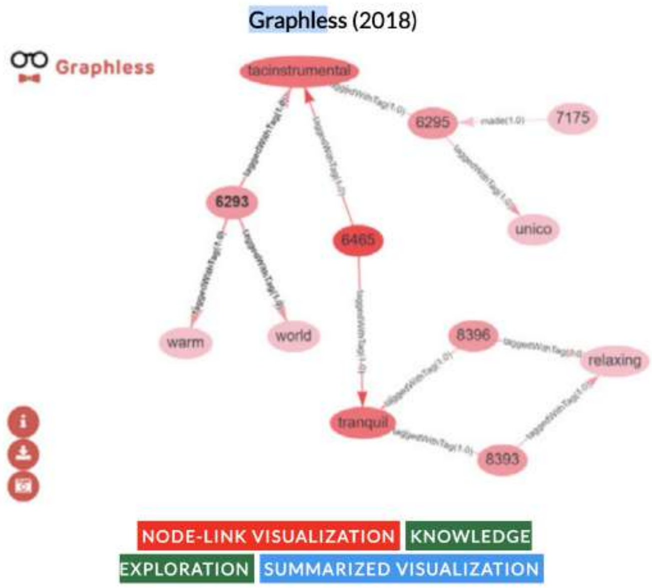

Figure 24. Graphless.

5. Semantic Annotations

Semantic annotations tools aim to annotate documents with entities, classes, topics or facts, typically based on an existing ontology/KB. Some works on Semantic Annotation include extraction and linking of entities and/or concepts (though not typically relations).

Methods to semantically enrich unstructured content can be classified in three main approaches [50]:

- manual;
- automatic;
- semi-automatic.

5.1. Manual

In the *manual* approach, humans are fully responsible for the semantic annotation of content.

For instance, **Omeka S** (https://omeka.org, accessed on 26 July 2023) (Figure 25) serves as a platform connecting digital cultural heritage collections with other online resources. Similarly, **SenTag** [51] provides an intuitive and user-friendly interface for tagging a corpus of documents. In manual systems, quality errors are primarily attributed to human input errors. However, the overall process throughput is limited by the amount of time knowledgeable individuals can dedicate to the task. Furthermore, it is essential to consider potential divergence in the criteria used for classification due to varying users' needs and perspectives.

AKTiveMedia [52] (Figure 26) is a user-centric system designed for annotating documents, supporting text, images, and HTML documents (containing both text and images) with ontology-based and free-text annotations. Both authors and readers can perform annotations, enabling the utilization of different ontologies. The annotations are stored separately from the document, along with authorship information, facilitating the sharing of comments and annotations with other community members through a centralized server. While most annotations are created manually, the system provides various techniques to reduce the effort required for annotating.

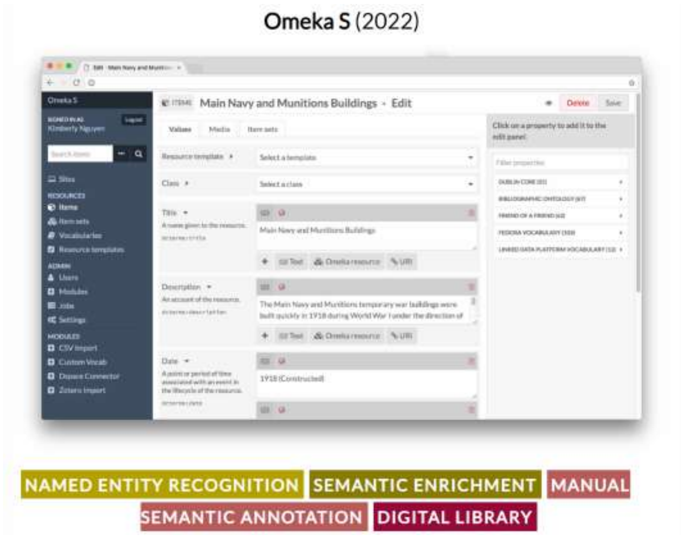

Figure 25. Omeka S.

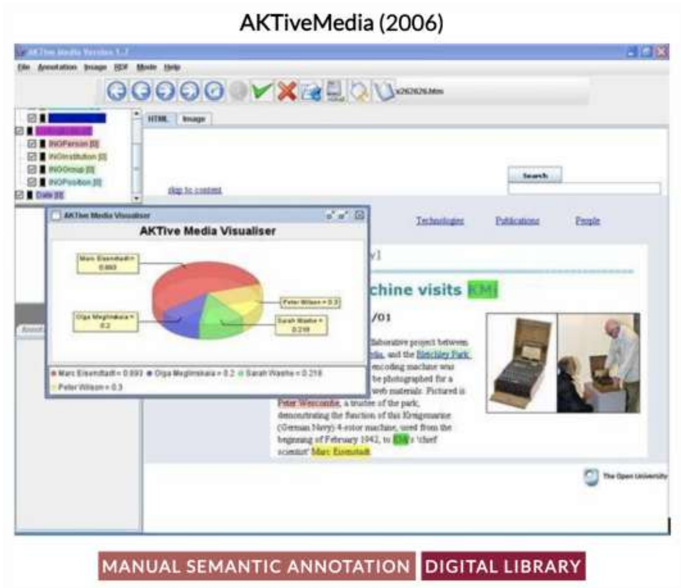

Figure 26. AKTiveMedia.

KIM [53] (Knowledge and Information Management) (Figure 27) platform comprises an ontology, a knowledge base, an automatic Semantic Annotation, indexing, and a retrieval server. Similar to SemTag, KIM's primary focus is to associate entities in the corpus with their semantic descriptions. It achieves this through the KIMO ontology, which contains named entity classes and their properties, and is pre-populated with a substantial number of instances. Annotations created in KIM are linked to the corresponding entity type and precise individual in the knowledge base. KIM offers a robust infrastructure capable of scalable and customizable information extraction, annotation, and document management. It is built upon GATE (the General Architecture for Text Engineering). To ensure a basic level of performance and facilitate the easy development of applications, KIM is equipped with an upper-level ontology and a knowledge base that provide extensive coverage of entities of general importance. From a technical standpoint, the platform enables KIM-based applications to benefit from automatic Semantic Annotation, content retrieval based on semantic restrictions, and the ability to query and modify the underlying ontologies and knowledge bases.

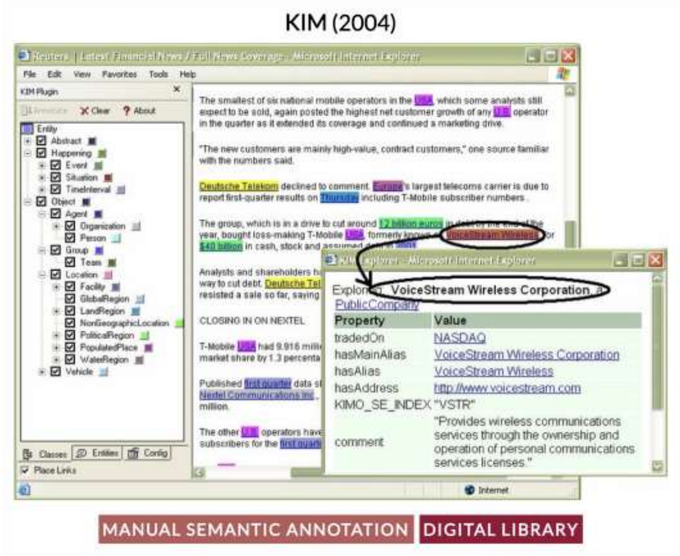

Figure 27. KIM.

Thresher [54] (Figure 28) empowers end-users, rather than content providers, to uncover the nested semantic structures hidden within web pages. It offers a web interface that allows non-technical users to quickly mark up examples of a specific class. Thresher then learns from these examples to automatically induce wrappers that can be applied to the same page or similar web pages. Thresher is specifically designed for web pages with similar content, focusing on the same type of object. Typically, web pages are supplied with relational data through a template, and Thresher extracts the corresponding information by analogy.

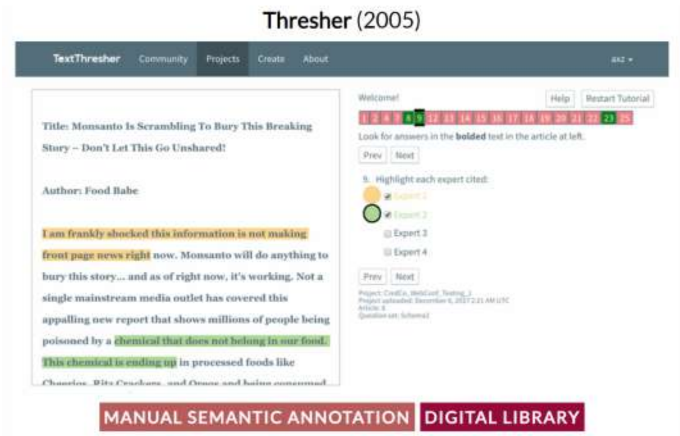

Figure 28. Thresher.

5.2. Automatic

Automatic methods leverage various techniques, including machine learning algorithms and natural language processing (NLP), to enable machines to derive semantic information from unstructured content with minimal user intervention.

For instance, **AnnoTag** [55] (Figure 29) provides succinct content annotations by utilizing entity-level analytics to generate semantic descriptions in the form of tags.

Similarly, the **Arca** [56] system (Figure 30) automatically associates unstructured content with concepts in a knowledge graph (KG). This enables complex queries on data and visualization of semantic associations connecting concepts and documents.

Figure 29. AnnoTag.

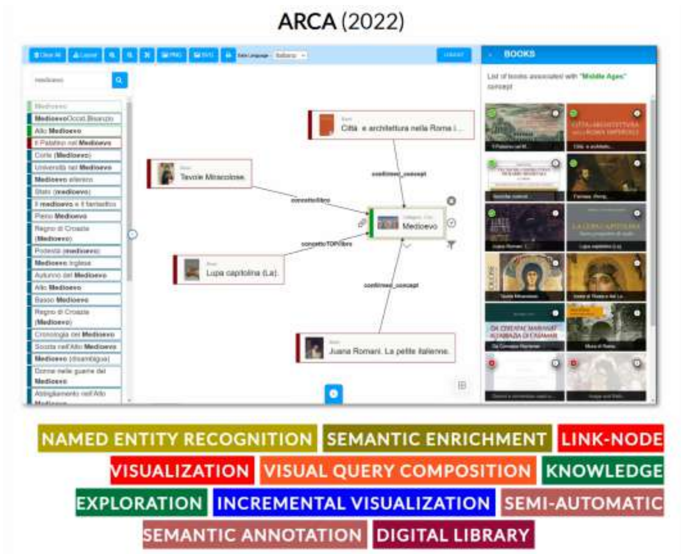

Figure 30. ARCA.

OpenCalais (http://viewer.opencalais.com, accessed on 26 July 2023) (Figure 6) is a web service that automatically generates comprehensive semantic metadata from unstructured text sources. Using NLP and machine-learning techniques, OpenCalais identifies entities in the text, which are further categorized into named entities, facts, and events. The tool enables the creation of maps (or graphs or networks) linking documents to people, companies, places, and other entities. OpenCalais is available for free, but there is a daily limit on the number of requests.

5.3. Semi-Automatic

Semi-automatic approaches aim to combine the advantages of both machine automation and human expertise, allowing collaboration between the machine and human experts while retaining human control over the final annotation results. An example of this approach is **tagtog** (https://www.tagtog.com, accessed on 26 July 2023) [57] (Figure 31), which is a collaborative tool for annotating texts. It offers features for searching documents and entities, but it lacks the capability to visualize relationships between entities.

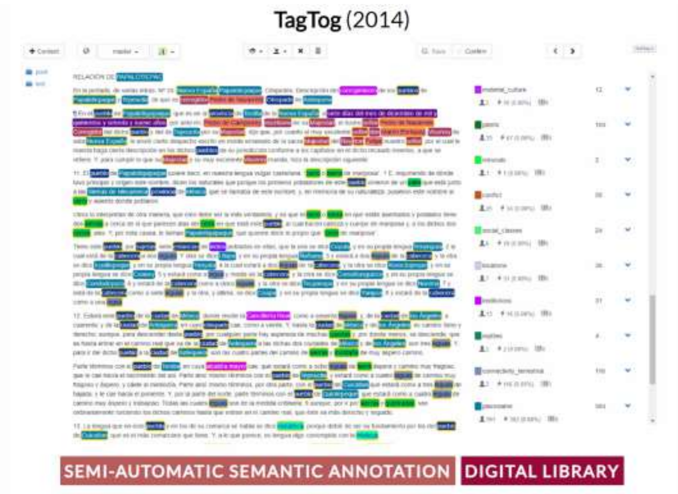

Figure 31. tagtog.

Recogito (https://recogito.pelagios.org, accessed on 26 July 2023) is an open-source annotation tool [58] (Figure 32) designed to foster connections between online resources that document the past. The tool enables users to annotate both text and images, including ancient maps and images in digital books.

Figure 32. Recogito.

GoNTogle [59] (Figure 33) presents a framework for Semantic ontology-based Annotations. It offers the capability to annotate various document formats, allowing annotations to be applied to entire documents or specific fragments. The annotations are stored in a centralized ontology server, keeping them separate from the original document. This framework supports both manual and automatic annotation. The automatic annotation feature utilizes a learning method that explores the user's past annotations and textual information to suggest annotations automatically. GoNTogle provides advanced searching capabilities by employing a flexible combination of keyword-based and semantic-based searches across different document formats.

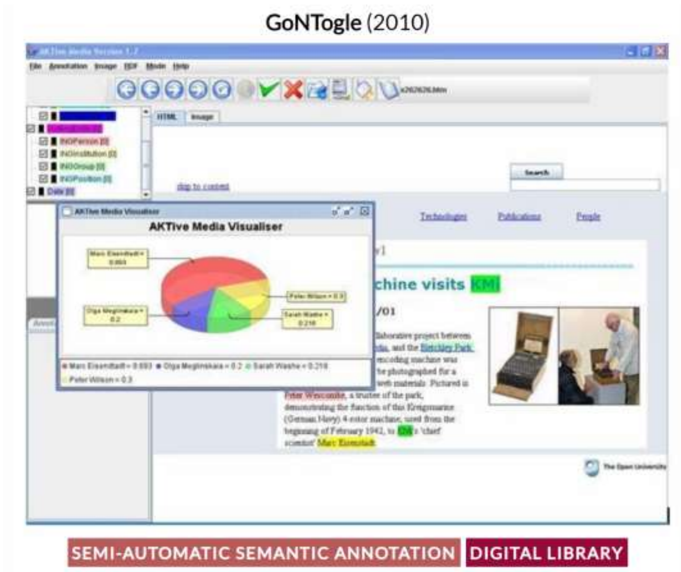

Figure 33. GoNTogle.

6. Exploration of a Digital Library

Within the expansive landscape of Linked Data interfaces, a distinctive subset of tools emerges, dedicated to fostering exploration and dissemination of knowledge within the realm of digital libraries. These tools stand apart by focusing on the specialized domain of digital collections, seeking to enhance users' engagement with the rich and diverse content found within these repositories. Unlike generic SPARQL endpoints that cater to a wide range of data sources, the tools within the *Digital Library* category are tailored to serve the unique needs of digital libraries. These tools go beyond the conventional approach of querying and retrieving data; they are designed to showcase the intellectual treasures embedded in library collections and provide users with an immersive experience that transcends mere data retrieval. By catering to digital libraries, these tools empower institutions to showcase their holdings, whether they encompass books, manuscripts, artworks, or multimedia resources. The primary objective is to facilitate the exploration and discovery of valuable insights and knowledge encapsulated within the library's catalog, making the library's offerings accessible to both casual visitors and dedicated researchers. Through sophisticated visualizations, intuitive interfaces, and user-centric functionalities, these tools transform the digital library into a dynamic and interactive space. Users can navigate through vast repositories, uncover hidden connections, and traverse the boundaries of disciplines and time periods. The tools in this category aim to democratize knowledge access, enabling users to embark on intellectual journeys tailored to their interests. Below, we delve into the intricate realm of digital libraries and the tools dedicated to enhancing the exploration of their collections. By examining the methodologies and features of these tools, we seek to shed light on their significance, impact, and the unique ways they contribute to the broader landscape of Linked Data interfaces.

Yewno Discover [60] (Figure 34) is an integrated system that provides classification and visual exploration of academic materials, offering valuable assistance to scholars in their research. However, this tool may lack adaptability and flexibility for diverse contexts of use, except with ad hoc adjustments. Moreover, in contrast to the proposed system, Yewno Discover makes limited use of the Knowledge Graph (KG) structure for exploration, which is a fundamental aspect of the research questions presented here.

Sampo-UI [61] (Figure 35) is a comprehensive framework that offers a collection of reusable and extensible components, application state management, and a read-only API for SPARQL queries. This framework enables the creation of a user interface for a semantic portal. Sampo employs various search paradigms, including free-text search, faceted search, geospatial search, and temporal search. It presents users with different views of search results, including tables, lists, geospatial visualizations, and temporal visualizations.

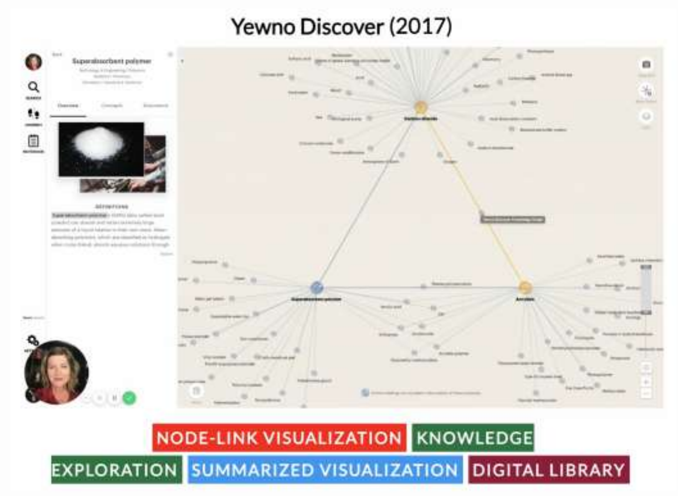

Figure 34. Yewno Discover.

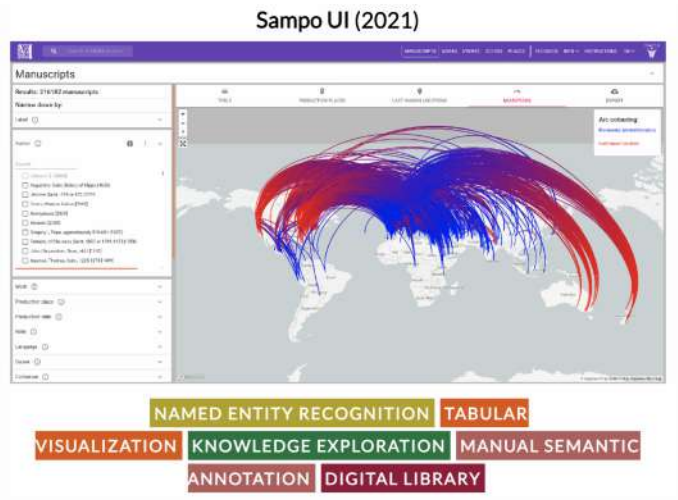

Figure 35. Sampo-UI.

Another tool used for exploring a digital library is **Talk to Books** (https://books.google.com/talktobooks, accessed on 26 July 2023), developed by Google. This tool allows users to explore ideas and discover books by obtaining quotes that respond to their queries. It aims to assist users in finding relevant books that might not be easily identified through traditional keyword searches. However, Talk to Books does not offer a way for users to autonomously explore the underlying knowledge base beyond the provided quotes. It focuses primarily on delivering book quotes in response to user queries rather than enabling direct exploration of the knowledge base.

Arca [62] (Figure 30) is a versatile platform designed for the exploration of knowledge within digital libraries. This modular software incorporates an engine for knowledge extraction and semantic enrichment, along with an interface that facilitates data search and exploration. The node-link visualization approach has been adopted as a central paradigm, employing a multi-level representation of information. Within this visualization, books and their associated contents are prominently highlighted, serving as a focal point for exploration. ARCA's interaction model follows an incremental approach, allowing users to navigate from specific information towards more general insights. This mode of interaction promotes serendipity, where unexpected information can be discovered through exploration and navigation of the graph. To further enhance the exploration process, Arca features a "trace path" component [63] that enables the creation of visual queries. With a trace path, users can identify common information between two selected items, such as books containing two concepts or concepts shared by two books. Moreover, ARCA integrates an association validation system [64] that facilitates collaborative efforts to improve data quality. This system enables users to contribute to the validation and refinement of associations within the digital library, fostering a collaborative approach to enhancing the accuracy and reliability of the available data.

7. Conclusions and Emerging Trends

Linked Data interfaces are constantly evolving, and several emerging trends are shaping their development. These trends are driven by technological advancements, changing user needs, and the increasing adoption of Semantic Web technologies. Throughout this survey of Linked Data interfaces, we have explored various categories of tools and discovered how they facilitate intelligent and intuitive exploration and querying of LD.

One prominent emerging trend is the integration of Artificial Intelligence (AI) and machine learning techniques into Linked Data interfaces. These AI algorithms enable automated semantic annotation, entity recognition, and knowledge extraction from unstructured content. Through these intelligent interactions, users can benefit from personalized recommendations, context-aware search results, and adaptive visualizations.

Another critical aspect is the understanding and interpretation of the insights generated by AI algorithms, which are being facilitated by the introduction of explainable AI. This feature is crucial in building trust in the system and ensuring the accuracy and reliability of the results.

Linked Data interfaces are increasingly embracing NLP, enabling users to interact with Linked Data resources using everyday language, breaking down access barriers and expanding the user base.

The adoption of emerging technologies such as Augmented Reality (AR) and Virtual Reality (VR) is redefining the exploration of LD, allowing users to interact with complex knowledge graphs in immersive 3D spaces.

Another important trend is the adoption of multimodal interfaces, combining different modes of interaction such as text, images, voice, and gestures. These interfaces respond to the preferences and needs of diverse users, offering a more inclusive and engaging experience.

Finally, the entire dataset collected during the analysis of the presented Linked Data interfaces in this survey is available on the website: https://linkeddata-89b9d.web.app (accessed on 28 August 2023). This website offers users the opportunity to iteratively explore and compare the various tools discussed in the survey, enabling them to experience and understand the different functionalities and approaches implemented by each tool. This online resource serves as a valuable reference point for in-depth knowledge of Linked Data interfaces and facilitates access and evaluation of the various available tools. Through this initiative, greater transparency and information sharing are promoted, encouraging collaboration and progress in the field of Linked Data interfaces.

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Data Availability Statement: The entire dataset collected during the analysis of the presented Linked Data interfaces in this survey is available on the website: https://linkeddata-89b9d.web.app, accessed on 28 August 2023.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

KG	Knowledge Graph
LD	Linked Data
NLP	Natural Language Processing
NER	Named Entity Recognition
NERL	Named Entity Recognition and Linking
AI	Artificial Intelligence

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