Visualisation of Ontology Changes and Evolution: A Systematic Literature Review

Romana Pernisch [a,b,*], Daniëlle Dijkstra [a,**] and Stefan Schlobach [a]
[a] *Department of Computer Sciene, Vrije Universiteit Amsterdam, Netherlands*
[b] *Discovery Lab, Elsevier, Netherlands*
E-mails: r.pernisch@vu.nl, danielledijkstra1998@gmail.com, k.s.schlobach@vu.nl

Abstract. Ontologies play an increasingly important role in organising knowledge. This comes with the challenge of keeping up with the changes within an ontology and the effect those changes have on the applications they are used in.Visualising changes can help users and ontology engineers alike to keep up with the evolution of an ontology, and selecting an appropriate visualisation tool can help this understanding process. However, determining a suitable visualisation tool can be challenging as there has been a plethora of tools and methods been introduces in the literature over the past two decades. This work provides a systematic overview of the existing ontology change visualisation tools by conducting a Systematic Literature Review (SLR), and analysing these tools w.r.t. their methods and availability. We identify 28 tools and methods among which we found three prevalent forms of displaying changes: *lists*, *graphs* and *statistics*. Of the 28 tools and methods, 12 tools are still available for use. Our analysis showed that in the earlier years, the focus of the visualisation was on displaying the changes, while in later years, the focus shifted to helping the user understand the changes and the greater picture of ontology evolution rather than individual changes. Our analysis provides a novel resource for selecting appropriate tools for visualising ontology changes and ontology evolution, and will enable researchers and practitioners to select the appropriate ontology change and evolution visualisation tools for their respective tasks.

Keywords: Survey, Ontology change visualisation, Ontology evolution visualisation, Visualisation tools

1. Introduction

Ontologies have become increasingly important in organizing knowledge in various fields, such as in the Biomedical field demonstrated by the Gene Ontology [1], the National Cancer Institute Thesaurus (NCIT) [2] or SNOMED CT [3]. With the rapid evolution of different domains and the frequent publication of new information, ontologies must be regularly updated by ontology engineers to ensure their relevance and accuracy. To illustrate the scale of the challenge, consider NCIT [2], which frequently undergoes updates as new drugs, drug usage, and disease variations are discovered and published, with *190.787 changes* on average *per month* between October 2003 and December 2019 [4]. In addition, the size of the ontology can make it difficult for users and ontology engineers alike to keep up with the changes. Therefore, it is crucial to provide visual representations and summaries that effectively communicate the evolution, enabling users to quickly adapt to the updated ontology.

There is a lack of a comprehensive understanding of the existing visualisation tools and methods available for communicating ontology changes, a systematic overview of such tools for ontology users and engineers is missing.

*Corresponding author.
**Equal contribution.

1570-0844/$35.00 © 0 – IOS Press. All rights reserved.

This is problematic, as effective tools for tracking and understanding ontology changes are crucial to ensure the continued relevance and usefulness of ontologies in various applications, including semantic search, natural language processing, and machine learning.

To close this gap, we conduct a Systematic Literature Review (SLR) to systematically identify the existing visualisation methods for ontology changes, which answers the following first research question:

RQ1: *What methods, approaches and implementations exist for visualising ontology changes?*

The overall goal of this research is to gather the existing visualisation methods and present a comprehensive overview of the different kinds of tools, hereby answering ***RQ1***.

Based on our SLR we identified 28 relevant tools which we further analysed focusing on different types of visualisation methods and objectives in relation to publishing time. This provides interest insights into how the visualisation objectives changed as the field matured. Further, we investigate the impact and popularity of a tool and if there is a relation between publishing time and format. Lastly, we report on which tools are still available or accessible (according to FAIR principles) and if this has something to do with when these were published or with their association with other tools like Protégé [5] or NeOn [6]. Hence, we formulate the following second research question with five sub-questions:

RQ2: *How do aspects of the found tools relate to the availability and publishing time of the tools?*

- ***RQ2.1:*** *Is tool popularity measured with citation count related to publication type, publishing time and availability?*
- ***RQ2.2:*** *Do the different tool objectives (visualisation of change, ontology evolution or other) relate to publishing time and their availability?*
- ***RQ2.3:*** *Do visualisation types of the presented tools relate to the time of publishing and their availability?*
- ***RQ2.4:*** *Does the interactiveness of tools present a relationship to the time of publishing and their availability?*
- ***RQ2.5:*** *How is the accessibility of the tools from the perspective of FAIR principles affected by the different aspects of the tools like publishing time, association with an ontology editing environment, interactiveness, visualisation objective and visualisation type?*

The SLR yielded a comprehensive overview of the 28 tools and methods related to visualisation of changes in ontologies. Certain tools like OntoAnalyzer [7], OnEX [8], EvoRDF [9], DIACHRON [10], Change Tracer [11], REX [12], and HGK [13] showed exceptional performance in showcasing ontology evolution beyond just changes. We found that the objective of showcasing ontology changes shifted from "simply" visualising the changes to informing the user about the evolution by aggregating changes in meaningful ways. We did not actually find a connection between publishing time, format, popularity, and the availability of the tools.

Therefore, we contribute the following findings with this work:

- An overview and comparison of 28 ontology change visualisation methods.
- An analysis of the trends within the 28 methods with regard to publishing time, publishing methods, availability of the tool, and the goal of the presented visualisation.
- An analysis of the methodology to highlight the importance of the chosen approach.

In the following section, we first discuss related work. In Section 3, we provide details on the SLR methodology, as well as on the analysis dimensions. The list of tools and their details are described in Section 4 followed by the analysis of trends in Section 5. Section 3.1 shows the analysis of our methodology. We discuss the limitations and future work in Section 6 and conclude this work in Section 7.

2. Related Work

Ontologies are broadly applicable for visualising data. An example of this is the CubeViz platform [14], where the authors utilise the RDF Data Cube ontology to represent statistical data. Most research discusses the importance of more research on the applicability of visualisation tools for ontology visualisation. Khattak et al. [15] highlight that changes within ontologies can be challenging to visualise and that a system or framework for visualising ontology changes is needed.

Dudas et al. [16] express the need for further research on ontology change visualisation tools. Their own research focused on finding flaws within already existing ontology visualisation tools and calls for enhancing them. Pernisch et al. [17] conducted a survey to determine users' preferences for representing changes and created ChImp, the Protégé plug-in that displays the impact of changes in real time. Furthermore, Pernisch et al. [18] also investigated the understanding of change impact by ontology engineers at editing time through a user study focused on the Protégé plug-in ChImp. The results of the user study showed that the plug-in improved the understanding of the change effects of the participants and that they felt better informed. This shows that ontology change visualisation tools are valuable in informing about the changes, and an overview of tools can help inform the public about the existing possibilities.

No research has been conducted yet on which methods for visualising changes in ontologies are most suitable overall. Chung et al. [19] conducted a small descriptive comparison of approaches, but did not look for approaches systematically and did not perform an evaluation with users. Therefore, a SLR of existing ontology change visualisation tools is the first important step. Ramakrishnan et al. [20] reviewed ontology visualisation tools and their effectiveness in end-user applications. They emphasise the importance of ontology visualisation for improving cognitive support for users. They focus on general ontology visualisation rather than visualising changes between versions of the ontology. Katifori et al. [21] also categorised ontology visualisation methods and expressed the need for more research to improve the usability and effectiveness of ontology visualisation methods. Therefore, to the best of our knowledge, our work is the first to conduct an SLR of ontology change visualisation methods.

The majority of research concerning ontology evolution visualisation primarily revolves around visualising changes within ontologies. Therefore, ontology changes and evolution are interconnected. It becomes crucial to provide a concise definition of what ontology evolution is. Haase and Stojanovic [22] present their perspective on ontology evolution as the process of adapting and changing an ontology to accommodate the consistent management of these changes. Flouris et al. [23] define ontology evolution as the process of changing an ontology according to a change in the domain or its conceptualisation. Zablith et al. [24] have discussed these definitions in their work, where they mentioned the need for a new way of defining ontology evolution. This new definition of ontology evolution consists of both changes made to an ontology and versioning of an ontology. In this research, it is crucial to relate these ontology evolution definitions to the visualisation of ontology evolution. Therefore, we later introduce a definition of ontology evolution visualisation which informs our information extraction about the tools within the SLR.

Lambrix et al. [25] formulate a set of functional requirements for ontology evolution systems. They also examine existing ontology evolution systems and their capacity to meet the desired functionality requirements, emphasising the role of visualisation. These discussions about the existing ontology evolution systems meeting the functionality requirements and visualisation show that it is important to discuss the level to which a system is capable of visualising ontology evolution. Showcasing differences between ontology versions can be considered ontology evolution visualisation. While Lambrix et al. [25] focus on evaluating established evolution systems in terms of visualising ontology evolution, it is worth noting that other ontology change visualisation tools might also possess the ability to showcase evolution within an ontology. Consequently, it becomes essential to create an overview of the ontology change visualisation tools and determine whether these tools are showcasing ontology evolution.

3. Methodology

In this section, we describe the methodology of the systematic literature review (SLR). This includes the approach of selecting the relevant primary studies to be included (to answer***RQ1***). We then summarise the process and present the high level numbers, before presenting the dimensions along which we analyse the included studies (***RQ2***).

3.1. Systematic Literature Review

The goal of this part of our methodology is to create an overview of existing ontology change and ontology evolution visualisation methods to first answer ***RQ1***. The list of tools that answer the research question is presented in detail in Section 4.

We used the guidelines for a systematic review of the literature proposed by [26–28] and adapted them to our use case. We first give a high-level explanation of our approach for a better understanding of the individual steps and decisions within the SLR as a whole. We then present further details about the following two aspects: the search strategy with the search string, followed by the inclusion and exclusion criteria along which we evaluate each publication.

High-level approach. Due to the lack of an overview of papers that could validate the results immediately, we opted for a circular approach rather than a linear one. The search string was executed in Scopus[1] where we used the "Title-Abstract-Keywords search". We chose Scopus as the search engine because of its ability to download results and its up-to-date and reliable indexing of research articles. The results were exported as a CSV file which was then used We evaluated according to inclusion and exclusion criteria and later for an extended analysis.

In the first step, we evaluated the title and abstract of each returned publication. In the second step, we analysed the entire publication, but only those that passed the first evaluation. Hence, the output of the second step yielded a list of publications that serve as primary sources for the SLR. This initial list was then used for the last step, snowballing, during which we evaluated incoming and outgoing 'links' to these publications using the same approach as before, evaluating each publication in two steps following the same inclusion and exclusion criteria. The resulting additional publications from the snowballing were added to the list of primary sources.

Search Keywords. The research question ***RQ1*** was used to come up with a fitting search string for the SLR, with the main keywords being: 'ontology changes' and 'visualisation'. We also added related synonyms and alternative spellings. We specifically combined certain keywords (instead of using AND), because we are interested in the keywords when they are included right next to each other and not simply anywhere in the text. Several variations of the search string were experimented with, aiming to strike a balance between generating a manageable amount of results and including the essential keywords. This resulted in the following initial search string:

> ("ontology change" OR "ontology evolution" OR "ontology changes" OR "ontology edits" OR "evolution of ontology" OR "changing ontology" OR "editing ontology") AND (visualisation OR visualisation OR visualizing OR visualising OR tool)[2]

Inclusion and Exclusion criteria. We defined the inclusion and exclusion criteria for selecting relevant articles from the candidate publications in Table 1. The criteria were documented before any decisions were made about the inclusion or exclusion of any publications. We merely revised the formulation to clarify its meaning and make this SLR more easily reproducible. The publications were evaluated by one author and, in case of doubt on inclusion or exclusion, a second opinion by another author was considered.

We distinguish between three main criteria (C1-C3) and describe and explain them in the table. **C1** focusses on the literature found, including a visualisation tool or approach. The goal of the presented tools should be to facilitate understanding of ontology changes. Additionally, with this criteria, we exclude surveys of tools from our SLR. **C2** is centred on exploration. We are also interested in including tools that not only present the changes, but also let the user explore and dive deeper to understand them. The accompanying exclusion criteria allow us to drop studies that do not provide enough details about how exploration is possible. Lastly, **C3** specifies that we are not interested in publications that present a change detection algorithm without also providing a way to communicate these to

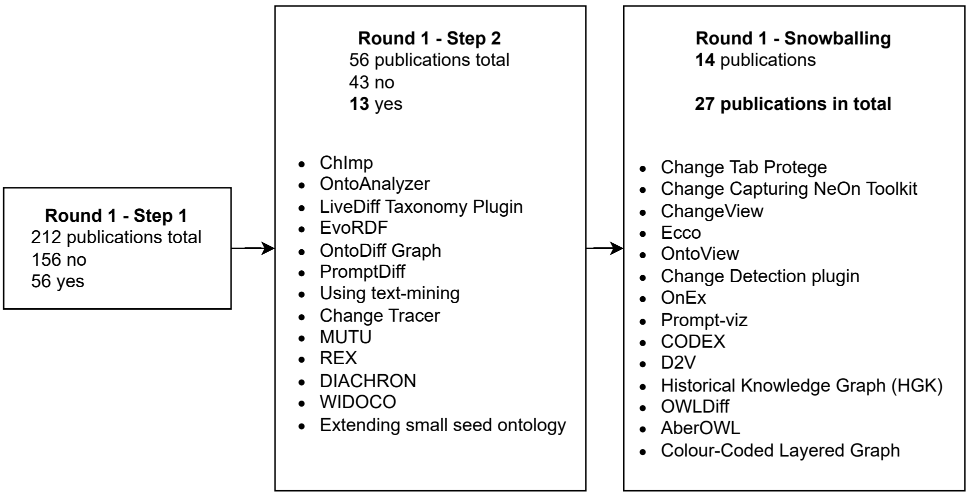
[1] https://www.scopus.com/search/form.uri?display=basic

users. Therefore, publications that only detail the algorithm that is used to calculate the difference between ontology versions will be excluded using this last criterion.

Table 1
Inclusion and Exclusion criteria for the SLR.

	Inclusion criteria:	**Exclusion criteria:**
C1	Studies that propose a visualisation tool/concept or technique/method for showcasing changes made to an ontology or the evolution of an ontology.	Studies that do not propose a visualisation tool/concept or technique/method for showcasing changes made to an ontology.
	We are interested in studies that present a visualisation technique/method or tool/concept that enables users to better understand and explore changes made in a system.	We are not interested in studies that simply provide a review or survey of existing visualisation tools.
C2	Studies that describe how the visualisation tool enables users to explore and analyze changes made in a system.	Studies that do not provide details about how the visualisation tool enables users to explore and analyze changes made in a system.
	We are interested in studies that provide details about how the visualisation tool works and how it enables users to explore and analyze changes made in a system.	We are not interested in studies that only describe the benefits of the visualisation tool without providing details about how it works.
C3	Studies where the tool/method communicates the changes.	Studies that are interested in algorithms that do change detection.
	We are interested in methods that communicate the changes.	We are only interested if it has visualisation added.

Process Results. Figure 1 shows the SLR process and the tools that were identified. In the first step we retrieved 212 publications, out of which 156 were discarded in the first step ("Round 1 - Step 1"). Of the remaining 56 that made it to the second step, we included 13 tools, which are listed under the respective step “Step 2”. During the snowballing process of Round 1, we further found and included 14 tools, as they are listed under “Snowballing”. Two papers in the SLR were excluded because of the unavailability of the full text after contacting the authors.



(a) Round 1

Fig. 1. Figures showing the process quantities of responses in the SLR and tools that were introduced in each round of the first phase of the SLR.

3.2. *Extended, Iterative, Search*

The relevant papers identified in the first round of the SLR constitute a valuable source of hitherto unexplored information about the search. Therefore we run a second iteration of the search, where we extend the original keywords by the most significant keywords in the abstract and title of the newly found papers.

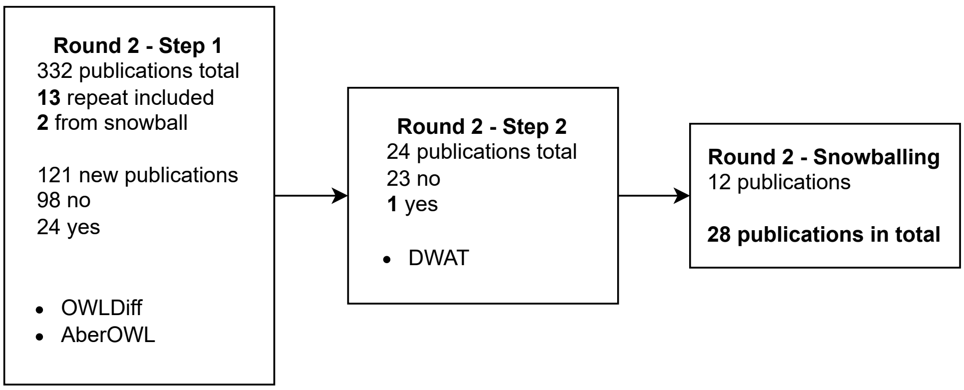
To this end, we analysed the list of primary sources using TF-IDF to identify the most important keywords and used those to revise the initial search string for a second execution in Scopus.

More concretely, we investigated the keywords used in the titles and abstracts of the tools listed under "Round 1 - Step 2" against those listed under "Round 1 - Snowballing" using Term Frequency - Inverse Document Frequency. A visualisation of the 20 keywords can be found in the Appendix in Figures 36b and 36c. Using this insight, we revised the search string and performed the SLR a second time as previously described using the same inclusion and exclusion criteria as defined before.

The following keywords were in common: "ontologies", "ontology", "changes", "versions", "knowledge", "change", "visualisation", "evolution", "data", and "users". The missing keyword, which can potentially make a large difference is 'versions' as well as some additional keywords that were not in common. Therefore, we expanded our initial search string with the keywords highlighted in **bold**.

("ontology change" OR "ontology evolution" OR "ontology changes" OR "ontology edits" OR "evolution of ontology" OR "changing ontology" OR "editing ontology" OR "**ontology versions**" OR "**ontology diff**" OR "**ontology versioning**") AND (visualisation OR visualisation OR visualizing OR visualising OR tool OR **environment**)[3]

Of the 332 articles we found this way, 211 were the same as in the first search, and 121 were new. First, the resulting tools of the old search were compared to the new search results. In the second round, we only list the tools that changed groups, meaning OWLDiff and AberOWL's publications were found among those retrieved, hence, they are listed under "Round 2 - Step 1". DWAT was additionally included through the investigation of the 121 newly retrieved publications and is therefore listed as the sole tool under "Round 2 - Step 2". As we did not perform a second snowballing during Round 2, the list below "Round 2 - Snowballing" is empty in the figure, but we would consider having found the missing 12 tools again, if not more.



(a) Round 2

Fig. 2. Figures showing the process quantities of responses in the SLR and tools that were introduced in each round of the second phase of the SLR.

Significant differences were added in the search string; however, the additions did not lead to finding significantly more relevant publications. Only two additional snowball tools were included in Round 2, not making a large difference between the TF-IDF plots of Round 1 and Round 2. In addition, we only found one additional tool not included in Round 1, DWAT [29]. This finding, however, we accredit to the fact that the publication time of this work was after the first execution of the Scopus search.

3.3. Analysis Dimensions

Once we have gathered the list of primary sources, we clarified the information to be extracted about each publication, as listed below. They are divided into *grouping criteria* and *analysis dimensions*. The dimensions and criteria presented were extracted from the selected publications after finishing the evaluations against inclusion and exclusion criteria.

Grouping Criteria. For each tool, we considered the way it visualised the changes between ontology versions. We identified three types of visualisation to classify the tools and methods: *List*, *Graph*, and *Statistics*. The *List* visualisation type is applied when a tool incorporates any form of a list to showcase changes. *Graph* visualisations can be very varying but refer to approaches that make use of graphical elements, specifically visualising nodes and their connections, rather than lists. Lastly, *Statistics* visualisations can be distinguished from other forms of visualisation when aggregation comes into play. They provide not just an aggregation per se, but also report the numbers and details of the said aggregation. Multiple visualisations can be used in combination; hence the grouping criteria are not presented as solely the three above but also as different combinations of them.

Analysis Dimensions. The following analysis dimensions were important to include for all the different tools and methods of the SLR overview to be able to answer ***RQ2***. The list below also explains the individual dimensions and how they were extracted from the primary studies. As the dimension of ontology evolution requires a definition, it is detailed after the list in a separate paragraph.

- *Publication Year*: The official year of publication. If no publication is associated with the tool, we use the first publication of the code or tool that we were able to find.
- *Publication Type*: Here we distinguish between journal articles, conference and workshop proceedings, and theses. Additionally, there might not be a publication associated with a tool, so this dimension is left empty.
- *Part or whole tool*: With this dimension, we capture if the tool as a whole is dedicated to showcasing ontology changes or if the ontology changes are only part of the tool but its aim is ultimately a different one.
- *Cited by* is the number of citations, which serves as an indication of its popularity in the analysis.
- *Interactive*: We indicate whether the tool is designed to be a static visualisation or interactive. Here, static does not mean that the visualisation itself cannot update, but if the user can actively interact and/or change how information is displayed.
- *Evolution*: In this dimension, we capture if the visualisation aims to inform the user about ontology evolution or if the focus is on simply displaying changes without additional information. A more detailed description is given after this list of dimensions.
- *User study*: We capture if a user study was included in the original publication of the tool. We do not investigate other types of study that were not included in the associated publication and therefore potentially conducted at a later point in time.
- *Plugin*: We indicate whether the presented tool is a plugin or a standalone tool.
- *Available*: We investigate whether the visualisation tool is still available today. We do this by locating either the source code or the application itself. However, we do not include if the codebase or application is still actively maintained, solely if it is still available for download.
- *Change Level*: This dimension captures if the tools focus on displaying all kinds of change or if the focus is on a class level only (indicated with ‘C’) dismissing individuals (ABox). This can be the case when tools are developed for specific disciplines where the ontologies used only make use of terminological information (TBox).
- *Data source*: In this dimension, we make a distinction between OWL and RDF, or in some cases, both can be mentioned as possible data sources for the tool.

Ontology Evolution. The ontology evolution dimension indicates whether a tool or method incorporates showcasing ontology evolution. To determine whether a tool or method incorporates this feature, understanding the definition of presenting ontology evolution and a stratification of the answers is important. Drawing from insights provided in Section 2, we need to formulate a definition of ontology evolution visualisation. Below, we provide an adjusted definition, that servetypess the purpose of defining boundaries within this SLR:

Representing changes in an ontology over time, where the change process is shown.

However, the words "over time" can encompass varying intervals. We distinguish between visualisation of ontology changes vs. evolution when visualisations focus on the process rather than just a comparison of two *consecutive* versions of an ontology. Hence, we indicate that a tool aims at visualising ontology evolution when it focuses on more than showing the differences between two versions.

4. Ontology Change Visualisation Methods and Approaches

The aim of this conducted SLR is to create an overview of the existing tools that visualise ontology changes or ontology evolution to answer ***RQ1***. All the resulting tools and methods of the SLR are divided into the groups previously defined in Section 3.3. In addition, we divide the tools on the basis of their interactiveness. All tools are summarised in Table 2.

4.1. List Visualisations

The following tools: Changes Tab (Protege) [31], Change Capturing (Neon-toolkit) [32], ChangeView [33], Ecco [35], WIDOCO [36], MUTU [34], Change Detection plug-in [30], and OntoAnalyzer [7] all gave an overview of all the changes within an ontology, in the form of a list. These tools can be divided into static and interactive tools.

4.1.1. Static List Visualisations

Changes Tab (Protege) [31], Change Capturing (Neon-toolkit) [32], and ChangeView [33] are all static *Only Lists* tools. These tools do not have any form of interactivity to their visualisation of changes. They all only show a list of changes. The following tools are very similar, they show a list of changes mostly with the change, time, author, and other relevant information in a table.

Changes Tab (Protégé). The Changes Tab in Protégé (2008) [31] allows users to keep track of all the changes and enables them to annotate those changes. The tab includes a table with a list of all changes, each change includes the following information: action (type of change), description (details of the action), author (person who made the change), and created (date and time the change was made).

Change Capturing (Neon-toolkit). The Change Capturing Neon toolkit (2008) [32] is a tool that allows users to visualise the changes that occurred within an ontology through a list of changes. The tool includes a table that shows the changes within an ontology in chronological order and shows the most relevant information regarding the change (author, time, and type of change).

ChangeView. ChangeView (2010) [33] is the Protégé view that shows a list of changes. This list includes a straightforward list of changesets, including the axioms that have been added and removed.

Table 2

All visualisation tools included in this systematic literature review ordered by kind of visualisation first, followed by publication year in ascending order. Legend: Change Level: Individuals (I), Classes (C), or Both (B), Source: ontologies (O), RDF datasets (R), or RDF/Ontologies (R/O).

	Year	Name	List	Graph	Statistics	other	Publication	Part	Citated-by	Interactive	Evolution	User Study	Plugin	Available	Change Level	Source
[7]	2005	OntoAnalyzer	✓				Conference	Whole	56	✓	✓				B	O
[30]	2006	Change Detection	✓				Thesis	Whole	28	✓	✓		✓		B	O
[31]	2008	Changes Tab	✓				Tool	Whole	N/A				✓	✓	B	O
[32]	2008	Change Capturing	✓				Tool	Whole	N/A						B	O
[33]	2010	ChangeView	✓				Tool	Whole	N/A				✓	✓	B	O
[34]	2011	MUTU	✓				Workshop	Whole	10	✓	✓			✓	B	O
[35]	2012	Ecco	✓				Workshop	Part	34	✓	✓			✓	B	O
[36]	2017	WIDOCO	✓				Conference	Part	140	✓	✓			✓	B	O
[37]	2008	Colour-Coded Layered Graph		✓			Journal	Whole	17		✓				B	O
[38]	2008	Extending small seed Ontology		✓			Workshop	Whole	1		✓				C	O
[39]	2011	OWLDiff		✓			Workshop	Part	48	✓	✓		✓	✓	B	O
[40]	2015	AberOWL		✓			Conference	Part	2	✓	✓			✓	B	O
[41]	2017	OntoDiffGraph		✓			Workshop	Whole	5	✓	✓			✓	B	O
[42]	2017	Live Diff Taxonomy		✓			Workshop	Whole	5	✓	✓		✓	✓	C	O
[13]	2020	Historical Knowledge Graph		✓			Journal	Whole	30		✓				C	O
[43]	2002	OntoView	✓	✓			Conference	Part	60	✓	✓				B	R/O
[44]	2004	PromptDiff	✓	✓			Conference	Part	169	✓	✓	✓	✓	✓	B	O
[45]	2004	Prompt-viz	✓	✓			Thesis	Whole	12	✓	✓	✓	✓		B	O
[11]	2013	Change Tracer	✓	✓			Journal	Part	56	✓	✓		✓		B	O
[10]	2016	DIACHRON	✓	✓			Workshop	Whole	2	✓	✓				B	R/O
[9]	2017	EvoRDF	✓	✓			Conference	Whole	14	✓	✓		✓		B	R/O
[46]	2012	CODEX	✓	✓	✓		Journal	Whole	31	✓	✓				B	O
[12]	2014	REX	✓	✓	✓		Conference	Whole	2	✓	✓				B	O
[47]	2015	D2V	✓	✓	✓		Demo	Part	9	✓	✓			✓	B	R
[48]	2007	Using text-mining		✓		✓	Journal	Part	12		✓				C	O
[8]	2009	OnEX	✓		✓	✓	Journal	Whole	44	✓	✓				B	O
[18]	2022	ChImp	✓		✓	✓	Journal	Whole	1		✓	✓	✓	✓	B	O
[29]	2023	DWAT		✓	✓	✓	Journal	Whole	0		✓	✓			C	O

4.1.2. Interactive List Visualisations

OntoAnalyzer. Rogozan et al. [7] introduced OntoAnalyzer in 2005. OntoAnalyzer is a tool that tracks and formalises changes in an ontology and analyses the impact of those changes to show the evolution effects. The tool provides a list of changes and enables clicking on the changes to get an explanation of the effect of these changes in text form (shown in Figure 3). OntoAnalyzer is highly capable of showcasing ontology evolution; the changes between two ontologies are shown. Clicking on these changes shows how these changes have occurred and the effect the changes have.

Change Detection plug-in. Plessers [30] introduced a change detection plug-in now named 'Change Detection plug-in' in 2006. In his thesis work, he proposed two plug-ins for Protégé, one plug-in automatically creates a version log, and the other plug-in implements the change detection mechanism and shows a list with an overview

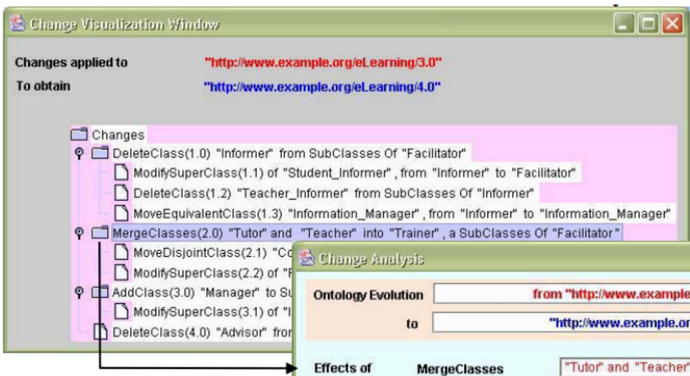


Fig. 3 (a) *Change Visualization window* shows the elementary and complex changes applied to V_N to obtain V_{N+1}.

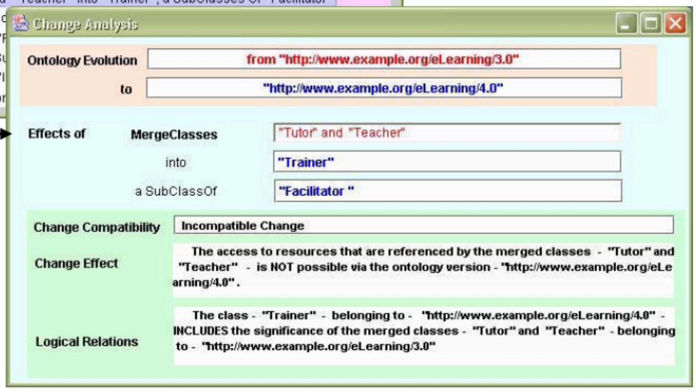


Fig. 3 (b) *Change Analysis window* illustrates an analysis example for a change that merged two classes from V_N into "Trainer" in V_{N+1}: (1) Change compatibility, (2) Change effect and (3) Logical relations among ontology versions.

Fig. 3. OntoAnalyzer visualisation of changes [7].

of all the detected changes (which can be seen in Figure 4). The overview also contains dropdown boxes, which the user can use to filter the detected changes by selecting a concept or the definition of a conceptual change. The Change Detection plug-in is generally capable of showcasing ontology evolution, the changes between two ontology versions can be further inspected with the dropdown box to show conceptual or concept change definitions.

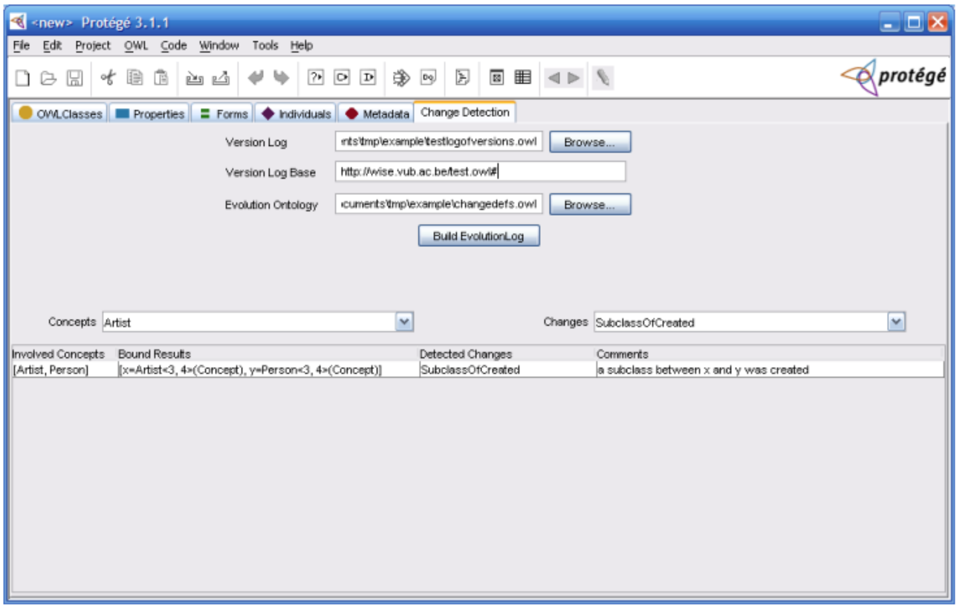


Fig. 4. Change detection plug-in visualisation of changes [30].

MUTU. Pessala et al. [34] introduced MUTU (2011), a tool that analyses changes and their potential effects. Figure 5 shows the visualisation of changes in MUTU. It shows an HTML format list that is sorted by interesting changes and the remaining changes. MUTU is generally capable of showcasing ontology evolution; the important changes between ontology versions show how an ontology has changed over time.

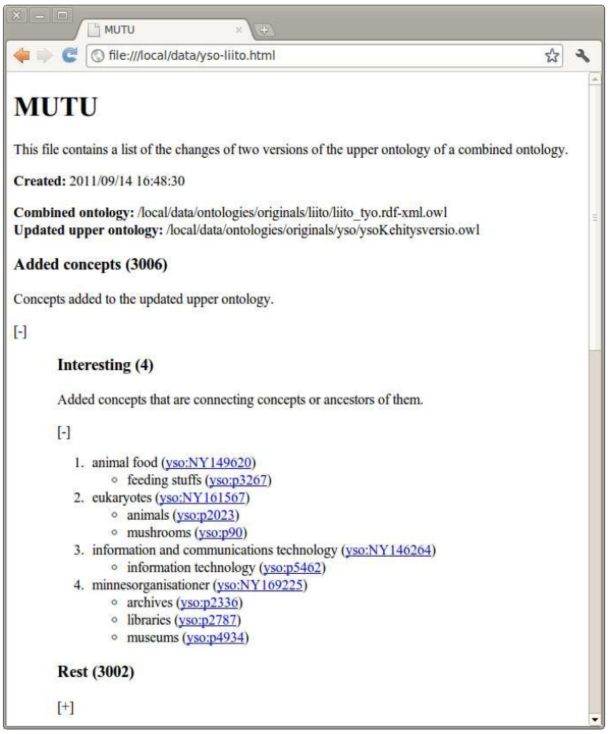


Fig. 5. MUTU visualisation of changes [34].

Ecco. Gonçalves et al. [35] introduced the Ecco tool (2012). Ecco is an ontology diff tool that helps users distinguish effective and ineffective changes within ontologies along with categorising their impact. Figure 6 shows the visualisation of Ecco; includes an HTML visualisation with a two-column layout. The right column shows the additions in green, and the left column shows the removals in the opposite colour (red). Furthermore, the changes are categorised into rewritten axioms, strengthened axioms, redundant axioms, weakened axioms, pure additions, and new descriptions. Clicking on these groups shows the explanation. Ecco is generally capable of showcasing ontology evolution, the changes are explained along with categorisations that show more information about the changes.

WIDOCO. Garijo [36] introduced the WIDOCO tool (2017) that includes a summary of changes. The changes within the object and data properties are shown. Furthermore, annotations are used to give more context to these changes and explain additional important information. WIDOCO specialises in detecting missing vocabulary metadata. It also shows a customised documentation of the ontology that can include different diagrams and other descriptions. WIDOCO is generally capable of showcasing ontology evolution, the tool includes information about the changes, and annotations that can help users understand more about the ontology evolution.

4.2. Graph Visualisations

Historical Knowledge Graph (HGK) [13], OntoDiffGraph [41], OWLDiff [39], AberOWL [40], Live Diff Taxonomy Plugin [42], Colour-Coded Layered Graph [37], and Extending small seed ontology [38] all fall into the *Only*

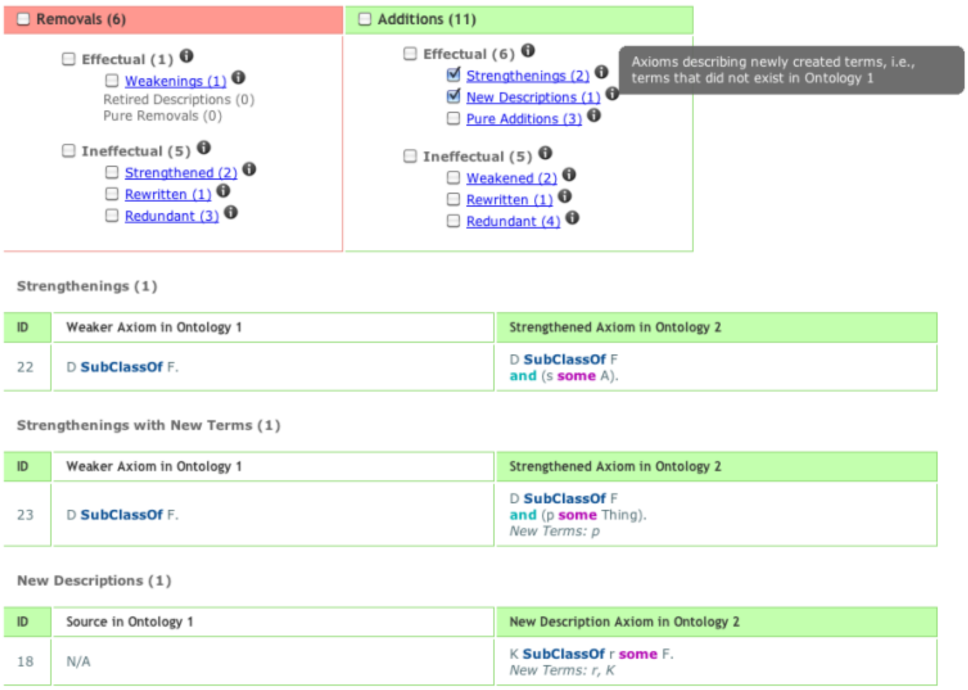


Fig. 6. Ecco visualisation of changes [35].

Graphs group. The Historical Knowledge Graph (HGK), Colour-Coded Layered Graph, and Extending small seed ontology are all static tools. However, these methods do not yet dive into the precise interaction type they involve, so this could change in the future. Ontodiffgraph, OWLDiff, AberOWL, and Live Diff Taxonomy Plugin are all interactive tools.

4.2.1. Static Graph Visualisations

Colour-Coded Layered Graph. Park et al. [37] introduce the approach of Colour-Coded Layered Graph in 2008 for a gene ontology. The graph visualises the differences between ontologies, which can be seen in Figure 7. The colours represent different actions: pink means different concept names, but use the same identifiers, red indicates removal, blue shows addition, grey indicates no change, 'is a' edge is blue, and 'part of' edge is orange. The approach can help visualise the evolution of an ontology, discover new insights, and possibly create hypotheses about the evolution of specific terms. The Colour-Coded Layered Graph is generally capable of showcasing ontology evolution; the evolution between two versions of an ontology is indicated with different colours.

Extending small seed ontology. Weichselbraun et al. [38] introduced the method of Extending small seed ontology in 2008. The method captures and visualises implicit data-driven ontology evolution. This is done by using ontologies that are semi-automatically generated through extending small seed ontologies. The ontology evolution is shown in a graph-like visualisation, which can be seen in Figure 8. The visualisation shows the evolution of 'oil' from November 2005 to August 2006. The size of concepts and numbers shows their importance. Dashed lines show that there are unnamed relations. The arrows show the relations. Extending small seed ontology is generally capable of showcasing ontology evolution; the ontology evolution is showcased with different colours, fonts, and sizes.

Historical Knowledge Graph (HGK). Cardoso et al. [13] introduced the Historical Knowledge Graph (HGK) method in 2020. The HGK visualises all the knowledge that an ontology consists of, as can be seen in Figure 9. The different versions of ontologies are updated within the HGK: deleted concepts get an end date, additions get a start date, and modifications are made. More complex changes are added, and the older version is deleted. Lastly,

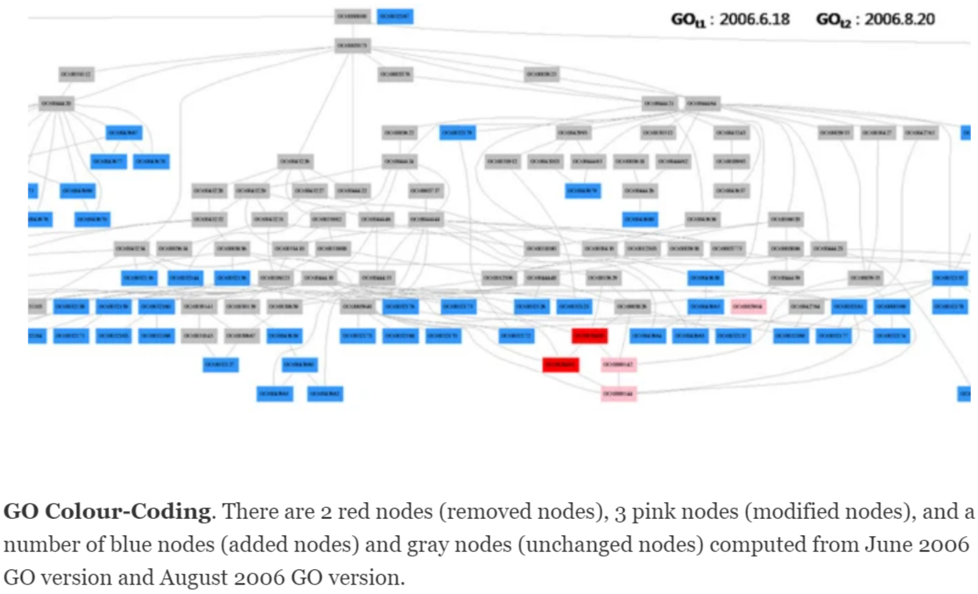


Fig. 7. Colour-coded layered graph visualisation of changes [37].

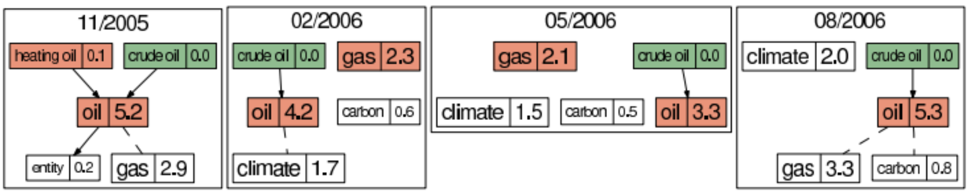


Fig. 8. Extending small seed ontology visualisation of changes [38].

evolutionary relations are added to aid users even more in understanding the evolution of an ontology. In Figure 9 dark blue changes are shown and light blue concepts stayed the same. HGK is highly capable of showcasing ontology evolution; the Historical Knowledge Graph shows the evolution of an ontology with dates, relations of evolution, and splits.

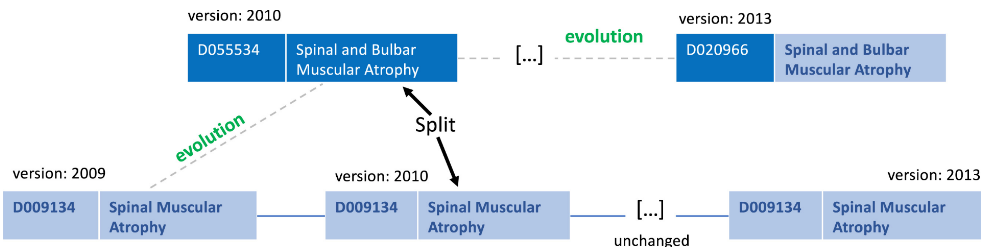


Fig. 9. HGK visualisation of changes [13].

4.2.2. Interactive Graph Visualisations

OWLDiff. Kremen et al. [39] introduced OWLDiff in 2011. OWLDiff is an ontology comparison and merge tool. The tool allows for different types of comparisons: syntactic, explanation-based, and semantic. Changes, additions, deletions, modifications, and redundancies are highlighted within OWLDiff. Figure 10 shows the trees in a side-by-side overlay view so that the user can visually see the changes between the older (left) ontology and the newer (right) version of the ontology. Trees can be represented as axiom lists, asserted frames (like ontology) and classified frames (like classified trees). The changes can be highlighted with different colours to show the type of change. OWLDiff is generally capable of showcasing ontology evolution; the evolution of an ontology is represented with different colours in a graph.

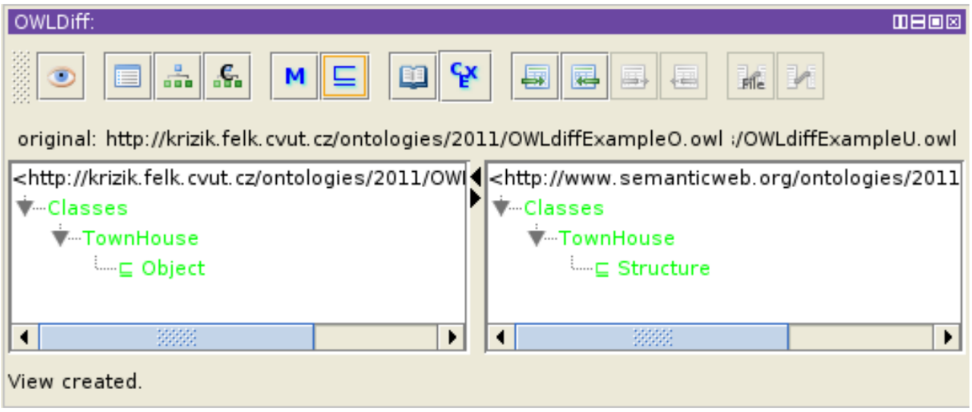


Fig. 10. OWLDiff visualisation of changes [39].

AberOWL. Rodrıguez-Garcıa et al. [40] developed AberOWL in 2015. AberOWL is a visualisation environment that showcases ontologies (biomedical), where automated reasoning is used to create a graph-based visualisation. The visualisation of a science ontology with the selection of a has unit can be seen in Figure 11. The tool is also capable of showing differences between the entailed axioms of different versions of ontologies. AberOWL not only visualises the direct changes, but also the inferences of the automated reasoning system. The differences are highlighted in different colours. AberOWL is generally capable of showcasing ontology evolution, ontology evolution can be seen in the graph with colours, and also inferences of the automated reasoning system.

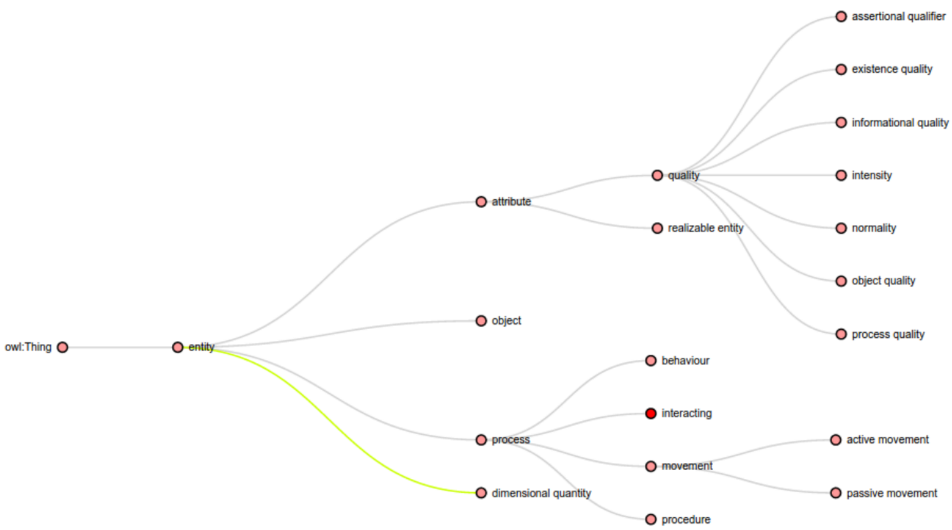


Fig. 11. AberOWL visualisation of changes [40].

OntoDiffGraph. Lara et al. [41] introduced OntoDiffGraph in 2017. It is a tool that shows a graph-based representation for identifying changes within an ontology. Differences between versions are highlighted with different colours, which can be seen in Figure 12. Creations, modifications, deletions, and the type of concept are visualised with different borders and colours; see Figure 12. The tool's menu shows all classes and properties from the ontology with colours that represent what happened to them (white = same, green = addition, blue = modification and red = removal). The tool allows users to zoom in and out, drag nodes, and the menu also allows users to find the specific concept in the graph. OntoDiffGraph is generally capable of showcasing ontology evolution, and the evolution of an ontology is represented with different colours in a graph.

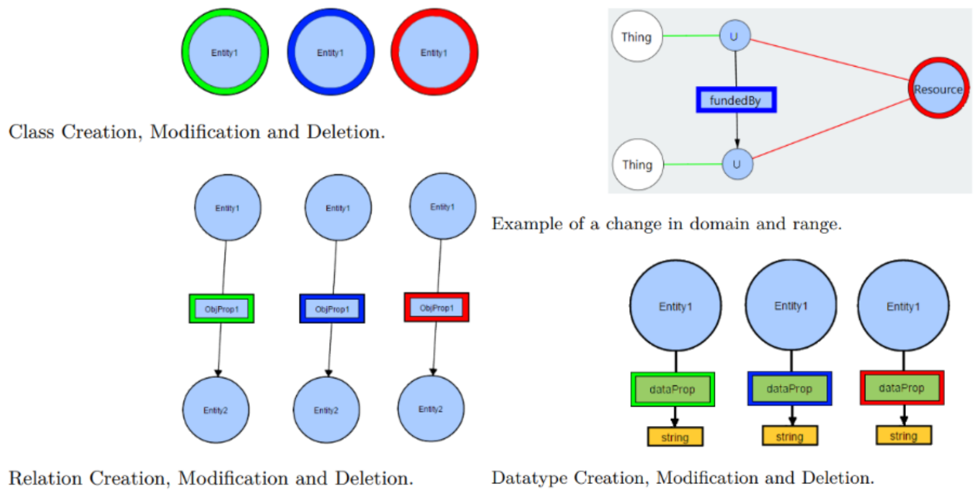


Fig. 12. OntoDiffGraph visualisation of changes [41].

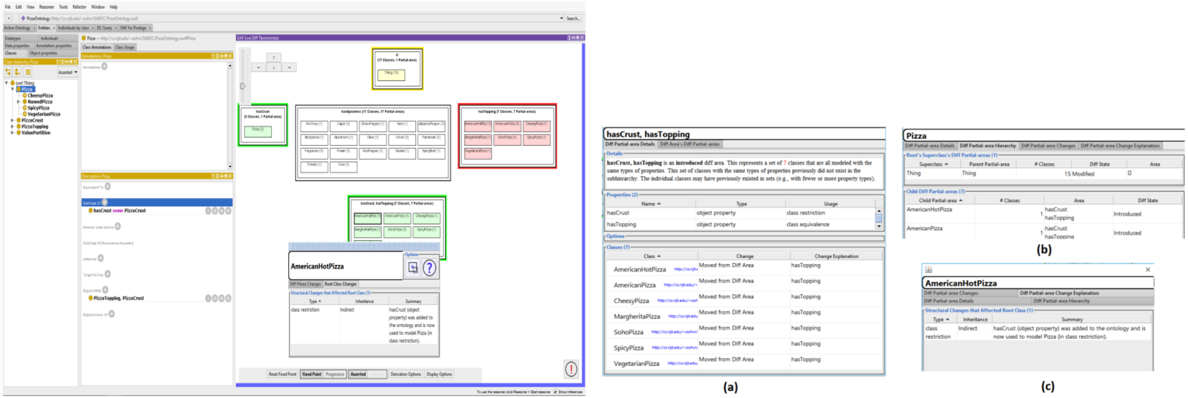
Live Diff Taxonomy Plugin (LDT). Ochs et al. [42] introduced the Live Diff Taxonomy Plugin (LDT) in 2017. The LDT plugin summarises and visualises changes within an ontology, which allows developers to further understand the impact their changes have on the ontology. Figure 13 shows the visualisation of Live Diff Taxonomies, which is a graphical diagram that shows diff areas and diff partial areas. Diff areas are boxes that provide a concise overview of changes made to sets of classes that incorporate the limitation of having the same property types. Diff partial areas provide a concise overview of changes made to particular subhierarchies within a diff area. Developers can click on the different boxes to get more information about what they represent, which is shown in Figure 13b for different diff areas and diff partial areas. Switching between the Protégé editor and the LDT plugin is made easy, since selecting a class within Protégé will centre that class as a diff area and vice versa. LDT is generally capable of showcasing ontology evolution; the diff-areas and diff-partial areas show the evolution of an ontology.

4.3. Visualisations combining Lists and Graphs

Prompt-viz [45], EvoRDF [9], DIACHRON [10], Change Tracer [11], OntoView [43], and PromptDiff [44] all fall into the *Lists and Graphs* group. All tools are interactive.

4.3.1. Interactive List and Graph Visualisations

OntoView. Klein et al. [43] introduced OntoView in 2002. OntoView is a change management system for ontologies, specifically for RDFS / DAML ontologies. A part of the tool shows two lists, next to each other, consisting of the components within an ontology in an RDF format-like structure. Changes between the two different versions of the ontologies are shown in bold letters as shown in Figure 14. The most interesting changes to the editor are



(a) Graphical diagram (b) More information

Fig. 13. Live Diff Taxonomy Plugin for visualisations of changes [42].

presented. Different highlighting colours are used to express different changes: non-logical change, logical definition change, identifier change, addition of definitions, and deletion of definitions. Moreover, to analyse changes, OntoView can highlight the places in an ontology where a modification has been made, upon request. OntoView is generally capable of showcasing ontology evolution, the interesting changes are shown between ontology versions, and on request these changes can be highlighted.

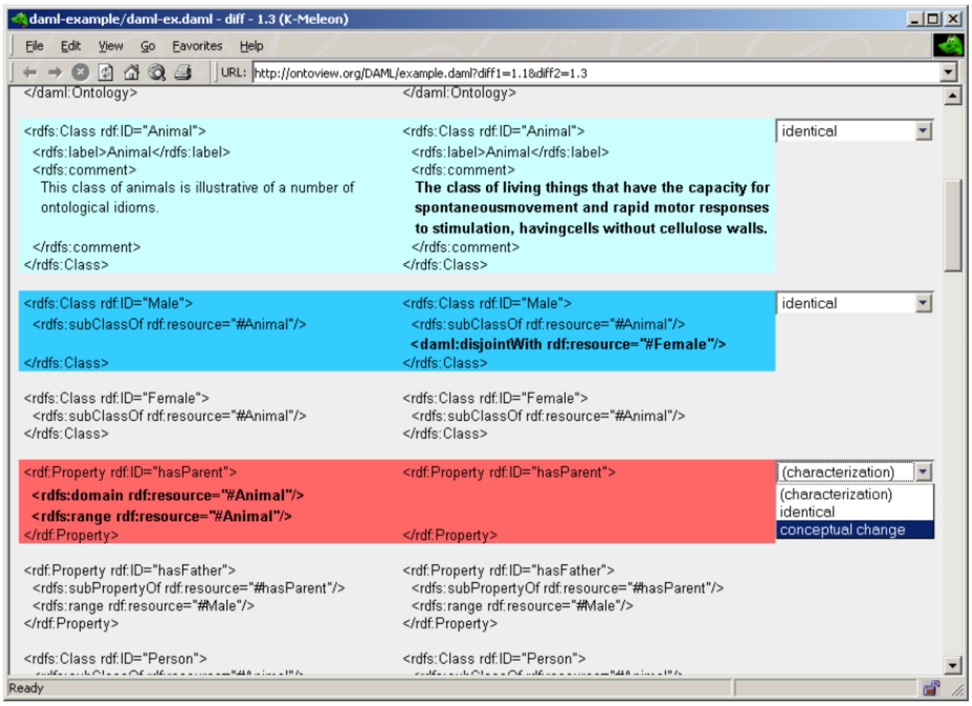


Fig. 14. OntoView visualisation of changes [43].

PromptDiff. Noy et al. [44] introduced PromptDiff in 2004. PromptDiff consists of a structural difference algorithm, an interface that enables users to visualise and analyse changes within ontologies, and features for change management. Changes are visualised through a class hierarchy and individual class changes. The class hierarchy shows that deletions are crossed out in red, additions are underlined in blue, and moved classes are grey in the old position and bold in the new position (shown in Figure 15.a). Individual class changes show the changes for the particular class that is selected (shown in Figure 15.b). PromptDiff is generally capable of showcasing ontology evolution, the ontology evolution is visualised with different colours and a class can be selected to show the ontology evolution within that class.

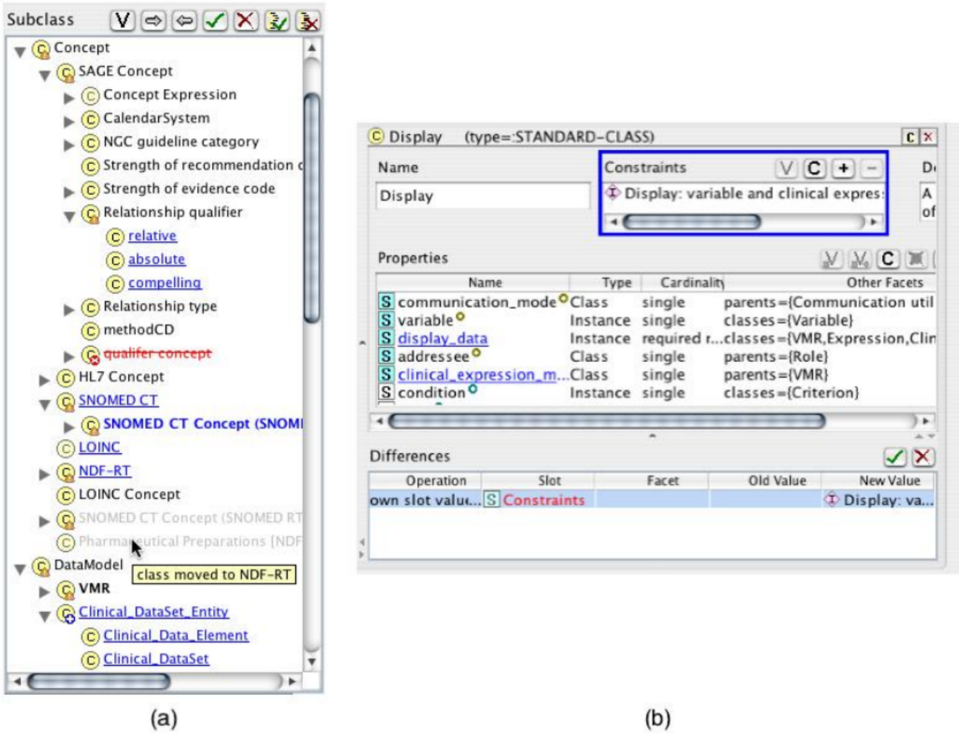


Fig. 15. PromptDiff visualisation of changes [44].

Prompt-viz. Stephen and Perrin [45] presented Prompt-viz in 2004. Prompt-viz is a Protégé tool that visualises changes within an ontology using treemaps. The tool shows the location, impact, type, and extent of changes within an ontology. Multiple visualisation components are used: Expendable Horizontal Tree, Treemap Layout, Path Window, and Detailed List of Changes. The Expendable Horizontal Tree presents a hierarchical tree structure where changes can be seen, shown in Figure 16 number 1. The Treemap Layout visualises the ontology as a set of rectangles that represent concepts within the ontology, shown in Figure 16 number 2. The size of each rectangle indicates the number of descendants, and the colour indicates the type of change. The Path Window shows the location and overview of the position within the ontology of the selected concept, shown in Figure 16 number 3. Lastly, the Detailed List of Changes shows the changes with information about the changes that occurred in the selected concept, shown in Figure 16 number 4. Prompt-viz is generally capable of showcasing ontology evolution, the Expendable Horizontal Tree, Treemap Layout, and Path window showcase ontology evolution.

Change Tracer. Khattak et al. [11] introduced Change Tracer in 2013. Change Tracer is a change management framework for evolving ontologies. Designed for users who want to navigate the evolution of an ontology. Two ways are used to visualise/explain changes within an ontology: tabular view and graph visualisation. The tabular view presents the change sets. Clicking on these change sets will produce the relevant information displayed in the

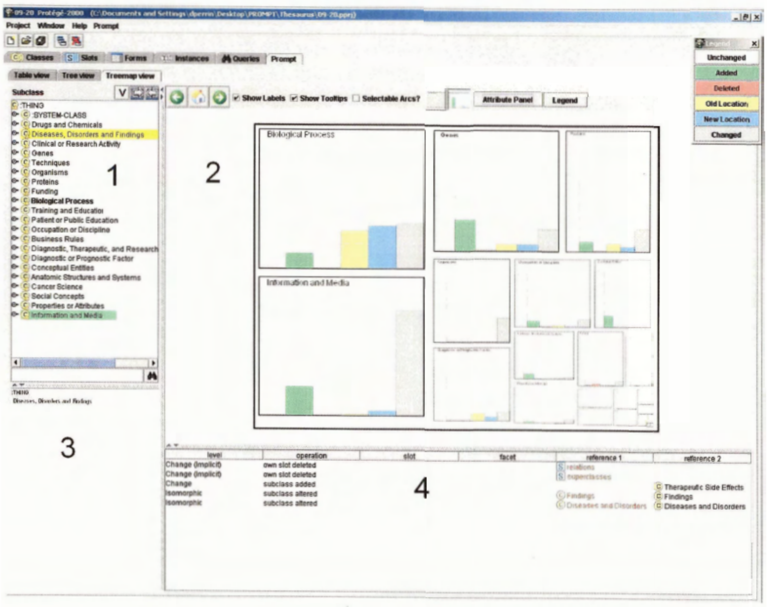
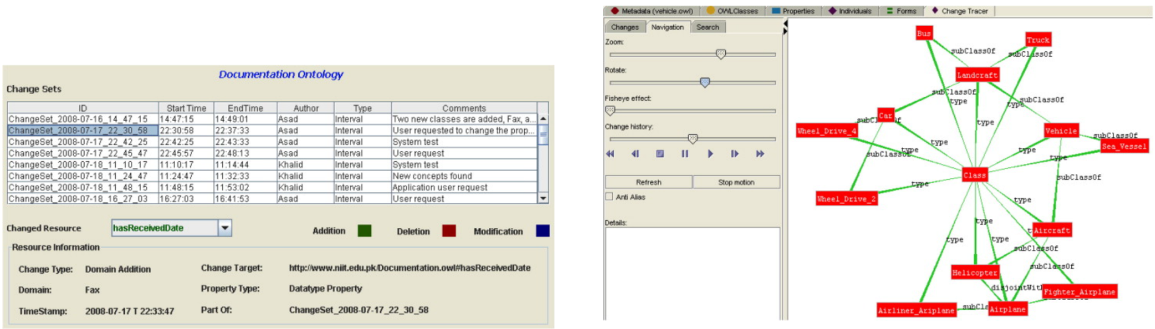


Fig. 16. PromptViz visualisation of changes [45].



(a) Change Logger Tabular View

(b) visualisation

Fig. 17. Change tracer visualisation of changes [11]

panel below, as can be seen in Figure 17a. Clicking on the dropdown box will show all the changes that occurred within the change set, and information about the selected change is shown. The graph visualisation shows the ontology, the changes within the ontology, and the effect that these changes have on the ontology, which can be seen in Figure 17b. The visualisation is a graph-like structure that is dynamic and interactive in showing classes (as nodes) and their relations (as edges). The directions of the edges are an indication of the direction of the relations. Ontologies can be visualised from the first version to the latest version. Changes are highlighted with colours. The deletions fade out gradually. Additions appear gradually. All of this helps users analyse trends and broaden their knowledge about the ontology evolution. The visualisation interface additionally provides the ability to zoom in and out and the fish-eye view. Change Tracer is highly capable of showcasing ontology evolution, the tabular view and graph visualisation show ontology evolution.

DIACHRON. Vrousgou et al. [10] introduced DIACHRON in 2016. DIACHRON informs users through ontology change visualisations and tracking the evolution of data in RDF format ontologies. The tool visualises changes between different ontology versions through a graphical interface, examples are shown in Figure 18. DIACHRON is highly capable of showcasing ontology evolution, it tracks terms and basic term metadata over time to show the evolution of an ontology or RDF document.

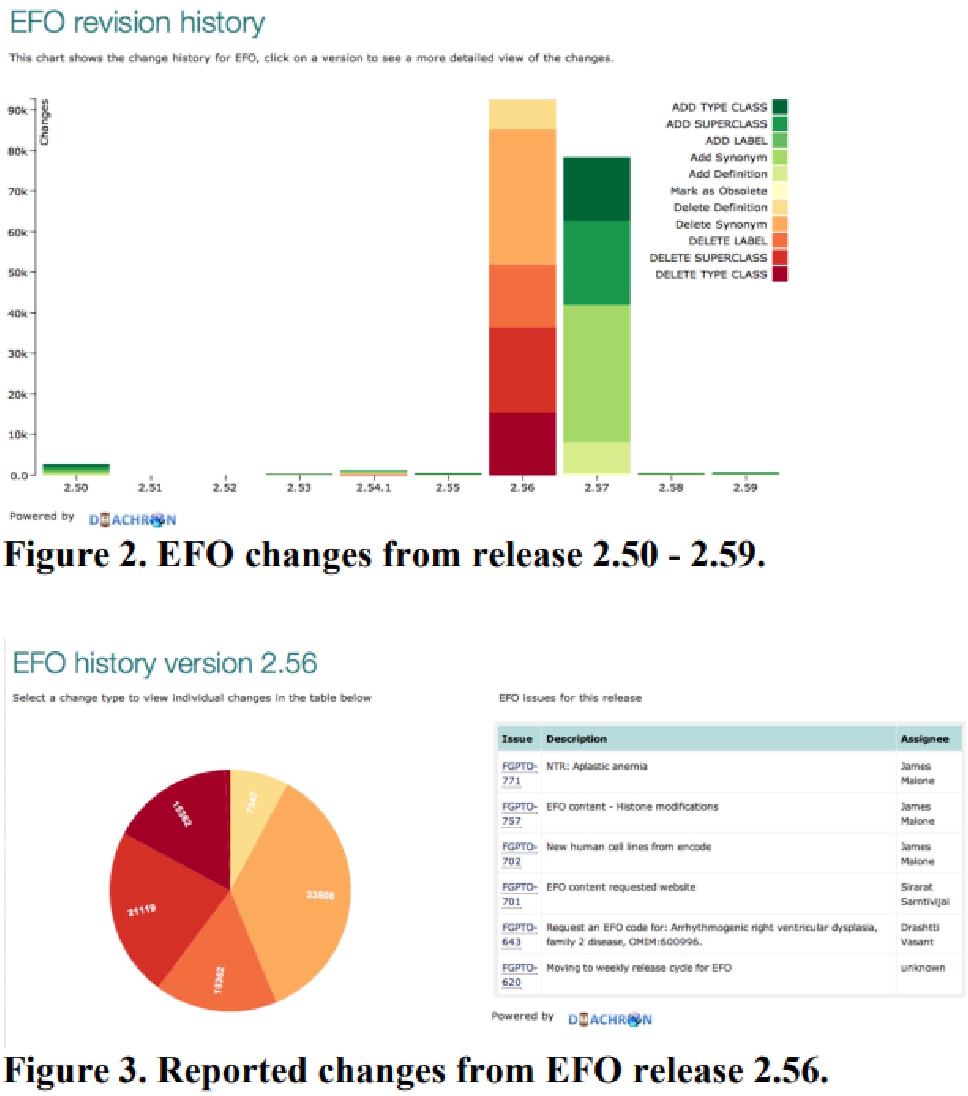


Fig. 18. DIACHRON visualisation of changes [10].

EvoRDF. Kondylakis et al. [9] introduced EvoRDF in 2017. EvoRDF is a tool that makes it possible to explore the evolution of an ontology using provenance queries. The Change Ontology consists of all the changes identified along with information about them, which can be seen in Figure 19.c. Different types of queries: *When*, *How*, and *Extended-how* can be answered through the EvoRDF Explorer shown in Figure 19.e or through the Protégé plug-in shown in Figure 19.d. *When* queries can answer a user's question about when a specific concept was introduced. *How* queries give more information on how a concept was created. *Extended-how* queries answer the question about what consecutive list of changes led to the creation of a specific concept. EvoRDF is highly capable of showcasing ontology evolution, *When*, *How*, and *Extended-how* queries can answer questions about what led to the creation of a specific concept. The consecutive list of change operations that led to a specific creation highly showcases ontology evolution.

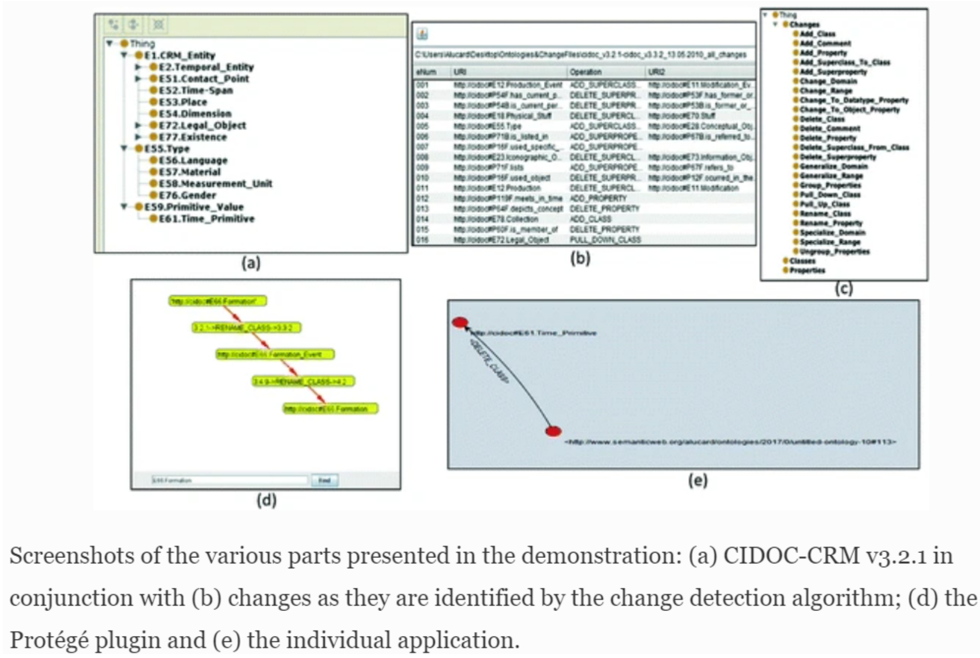


Fig. 19. EvoRDF visualisation of changes [9].

4.4. *Visualisations combining Lists, Statistics, and Graphs*

CODEX [46], D2V [47], and REX (Region Evolution EXplorer) [12] are tools or methods that fall into the *Lists, Statistics, and Graphs* group. All tools are interactive.

4.4.1. *Interactive List, Statistics and Graph Visualisations*

CODEX. Hartung et al. [46] introduced the CODEX tool in 2012. CODEX (Complex Ontology Diff Explorer) is a tool that uses its diff algorithm to describe and explain changes in the Web application. Input section A shows all the input possibilities for the ontologies, which can be seen in Figure 20. The result section B (1-5) shows all the ways that the changes can be visualised/explained. B1 shows the overall statistics, like the number of concepts and relations, diff sizes (occurrences can be visualised in a pie chart), and growth rates. B2, the change explorer, shows the most frequent changes or elements that have been influenced by a change. These changes can be clicked on and explored in a tree-like manner, which shows more information about the relations and details of the change. B3 the change navigator shows a similar visualisation as B2, where all changes can be explored. B4 shows the change impact where users can explore whether a concept was influenced by a change. B5 allows users to download/export results (changes) of the diff algorithm to reuse in othervisualisationsn/reports. CODEX is generally capable of showcasing ontology evolution, and it can be analysed through the diff results.

REX (Region Evolution Explorer). Christen et al. [12] introduced REX (Region Evolution EXplorer) in 2014. REX helps users visualise and understand the evolution of changes that occurred in ontologies. REX uses three ways to show / analyse changes within ontologies: *Structural Analysis*, *Trend Analysis*, and *Quantitative Change Analysis*. The *Structural Analysis* visualises a graph of the evolution of an ontology over a specific time period, shown in Figure 21. Each node represents a concept, and each edge represents an is-a relation. Changes are visualised by highlighting the changed regions together with an indication of the intensity of the changes. Rex uses a region discovery algorithm so that the graph can be visualised (Browser view in Figure 21a). The Browser View graph visualises the concepts in a circular way, descendants and parents of concepts are visualised closely. The graph enables a user to select a concept to show the regions related to that concept. The selected concept will be the central node in the Browser View graph. The colour within the graph showcases which regions are stable and which

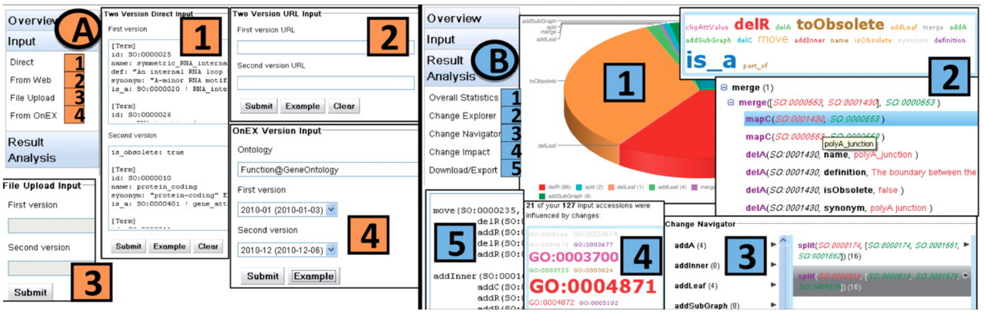
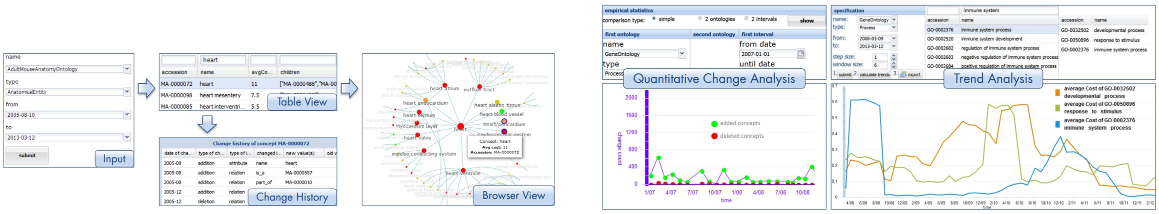


Fig. 20. CODEX visualisation of changes [46].



(a) Structural analysis component (b) Quantitative Change and Trend Analysis component

Fig. 21. REX visualisation of changes [12].

are unstable. Red shows that a region has a higher change intensity, while green shows a stable region. Both the Table view and Browser view allow users to navigate through interesting concepts or subregions. The Table View allows search criteria to be used to find the region of interest. The Change History component shows an overview of all the changes that occurred. Figure 21b shows the *Quantitative Change Analysis* and *Trend Analysis*. The *Quantitative Change Analysis* shows numerical measures that present information about how many changes occurred within a certain time. The different types of changes (deletion, addition, etc.) can be analysed. Rex uses the trend discovery algorithm to find the trends within the ontology. The *Trend Analysis* informs users by displaying trends within regions to show the evolution of specific regions. Users can specify which ontology should be analysed, what time interval they want to use, how many different versions of an ontology they want to include, and the region that should be analyzed. A line chart is used to visualise the trends (average costs), which enables users to analyse the change intensity. REX is highly capable of showcasing ontology evolution, the *Structural Analysis*, *Trend Analysis*, and *Quantitative Change Analysis* all showcase ontology evolution.

D2V. Roussakis et al. [47] introduced the D2V tool in 2015. D2V is a tool that assists users with an interactive visualisation interface that analyses the evolution of datasets, specifically for dynamic RDF datasets. The tool has different views in which it shows the evolution history: dataset-centric, version-centric, change-centric, and term-centric. Different views can be visualised through different types of chart: pie, column, bar, line, and area. A table is provided as well with a list of changes, where filtering on change types and versions is possible. Clicking on parts in each chart or table enables further analysis, revealing additional details. An example of a data-centric and version-centric view is shown in Figure 22. D2V is generally capable of showcasing ontology evolution; it can be analysed with dataset-centric, version-centric, change-centric and term-centric views.

4.5. Mixed Visualisation Approaches

ChImp [18], OnEX [8], and Using Text-mining [48] are all tools and methods that fall into the *Mix* group. ONEX is interactive. ChImp and Using Text-mining are more static.

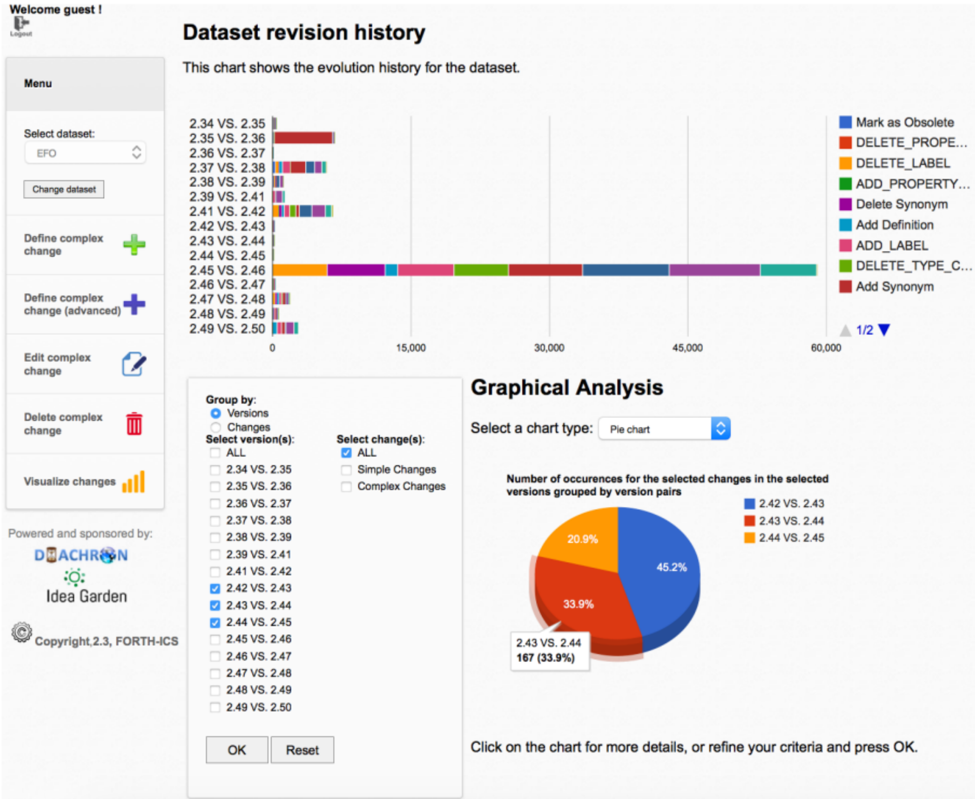


Fig. 22. D2V visualisation of changes [47].

4.5.1. *Static Mixed Visualisation Approaches*

Using text-mining. Enkhsaikhan et al. [48] introduced the Using text-mining method in 2007. They presented an approach that measures and visualises ontology concept clusters at different times and shows tables that further inform users. They used a specific ontology in the media domain of Australia, however, it could be useful to some other ontologies. One example by Enkhsaikhan et al. is shown that can be seen in Figure 23 (6.7.8). Figure 6 shows the scaled circles that indicate the amount of attention each topic receives from the media. Figure 7 zooms into a cluster (politics) in different periods. Figure 8 shows the different percentages of contribution of certain concepts. More visualisations are included, like the actual clusters of each point in time, a cluster weights table with the date, and a similarity measurement table with dates. Using text-mining would be generally capable of showcasing ontology evolution, and the graphs and tables visualise the changes between ontology clusters at different time periods to help understand the overall ontology evolution.

ChImp. Pernisch et al. [18] investigated their ChImp tool in 2022. ChImp stands for 'Change Impact', which is a Protégé plug-in that displays information related to changes within an ontology. The information displayed consists of the Change Display, Impact Display, and Metrics Table. The Change Display shows the most recent change made and the previous changes below. All displays can be seen in Figure 24 under the numbers 1, 2, and 3. The Impact Display shows the internal reasoner to indicate the consistency status of the ontology and the materialisation impact measures to show the impact of changes on the ontology. Impact measures of materialisation include the size-based impact and the change-based impact. The size-based impact quantifies the extent to which the materialisation between two ontology versions changes. Change-based impact illustrates the impact of an average change in the ontology. The Metrics Table shows primitive and composite metrics; users can choose whether all changes or the last change should be shown, and whether metrics using absolute numbers or percentages should be shown. Finally, a simple line chart shows the change of metrics. ChImp is generally capable of showcasing ontology evolution; the

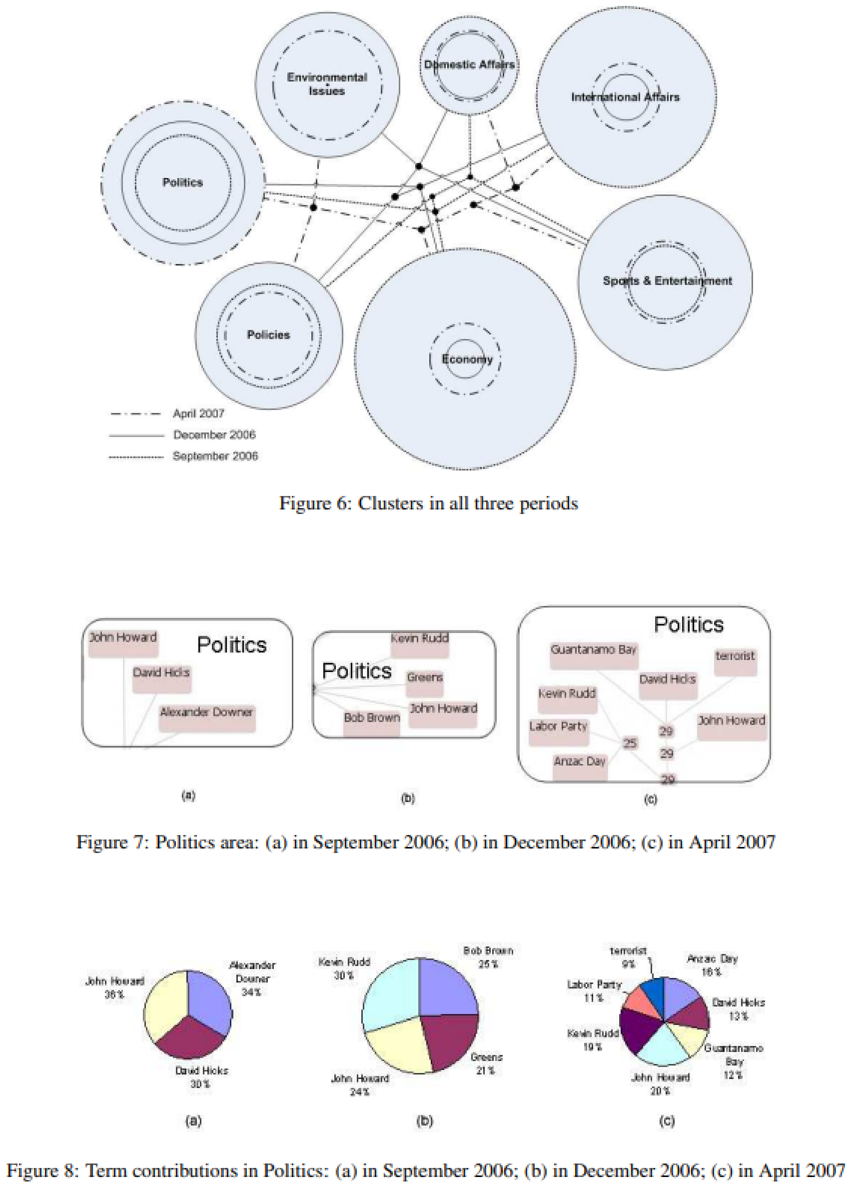


Fig. 23. Using text-mining visualisation of changes [48].

Change Display, Impact Display, and Metrics Table all aid users in understanding more about the evolution of an ontology.

DWAT. Zheng et al. [29] present the Diff Weighted Aggregate Taxonomy (DWAT) to help understand changes between two versions of an ontology. They demonstrate how DWAT works, as well as its benefits in the use case of Coronavirus Infectious Disease Ontology (CIDO). The goal of this visualisation is to present the "big picture" of the changes between versions. DWAT is based on multiple previous works, first on that of Ochs et al. [42], who introduced the partial diff area taxonomy. However, their approach still proved to be unscalable for the application of the CIDO ontology. Therefore, Zheng et al. make use of the Weighted Aggregate Taxonomy (WAT) instead. They define the weight of a partial area as the number of descendant concepts of its root 'r' in the whole ontology. Only

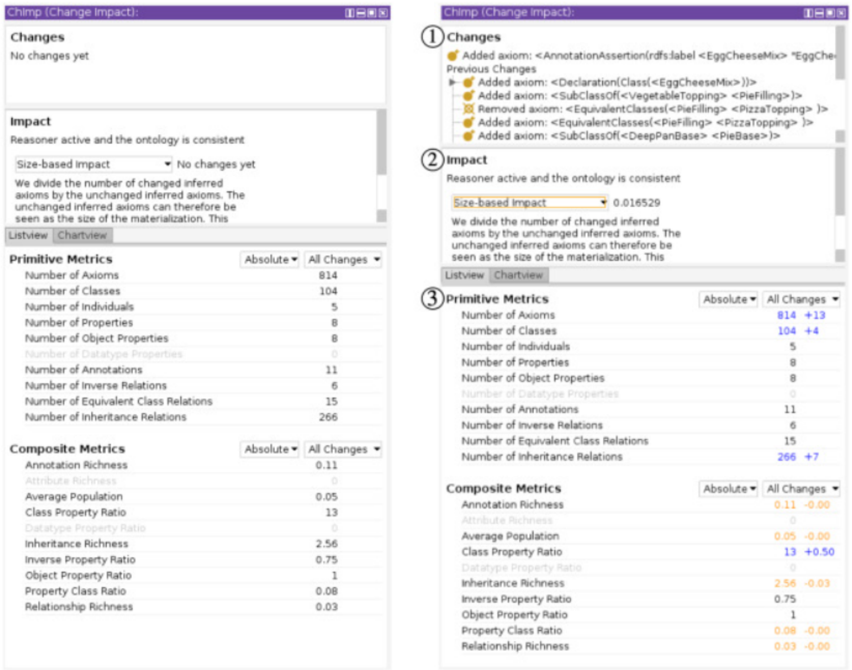


Fig. 24. ChImp visualisation of changes [18].

partial areas which have a weight higher than or equal to b are displayed, and those smaller ones get aggregated to the closest larger area and are therefore not lost. The difference between DWAT and DPAT is that DWAT needs to record not only the changes in the number of concepts, but also in partial areas and relationships. DWAT also enables a "drilling-down" to further explore the changes, similar to DPAT. The drawback of this approach is that it is not suitable for small ontologies. DPAT can easily aggregate the information without loss of detail and there is no need for additional weighting.

4.5.2. Interactive Mixed Visualisation Approaches

OnEX. Hartung et al. [8] introduce OnEX in 2009. OnEX (Ontology Evolution EXplorer) enables users to visualise changes within an ontology in three interactive workflows: Quantitative Evolution Analysis, Concept-based Analysis, and Annotation Migration. *Quantitative Evolution Analysis* gives users an overview of the evolution of an ontology; see Figure 26a. OnEX allows a selection of ontologies to be used. This workflow presents a trend chart that shows the evolution of an ontology, provides a summary of changes statistics for each ontology, and allows further investigation of the different types of changes between ontology versions. *Concept-based Analysis* visualises a detailed analysis of changes for specific concepts, which can be seen in Figure 26b. The search panel can be used to access specific desired concepts. This workflow shows the available information and history of the specific concept. *Annotation Migration* aids in the migration of annotations to a newer version of an ontology, shown in Figure 26c. Differences between versions of ontologies are analysed and these adapt the annotations. Moreover, users can delete/update annotations that are based on the changes the system detected. OnEX would be highly capable of showcasing ontology evolution because the Quantitative Evolution analysis workflow showcases the evolution of an ontology over time.

5. Comparison and Analysis of Ontology Change Visualisation Methods

We answered ***RQ1*** with the above list of tools, approaches and visualisation methods as well as their descriptions. This section presents the analysis and comparison along the dimensions previously presented to answer ***RQ2***: *How*

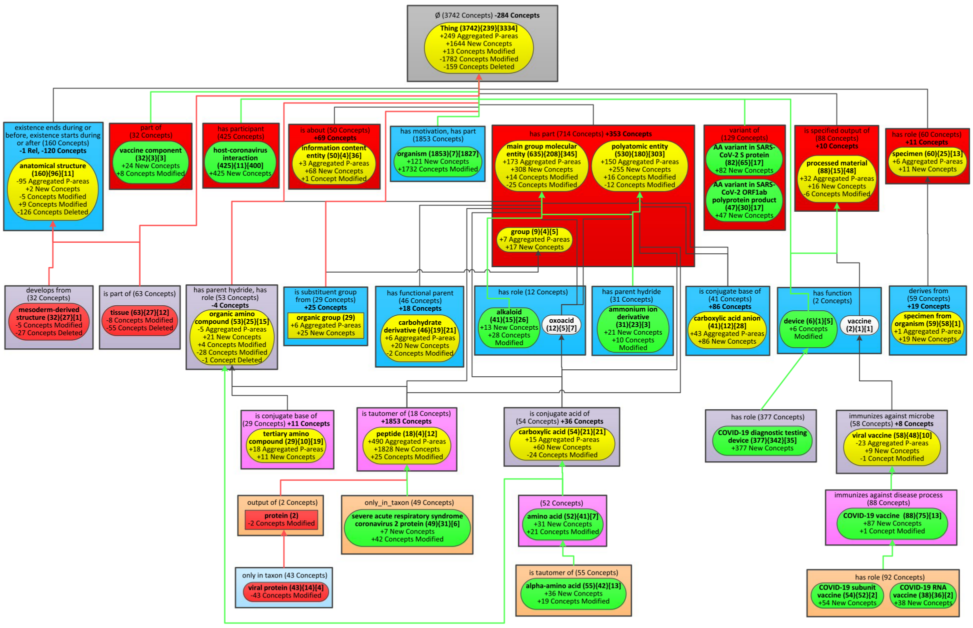
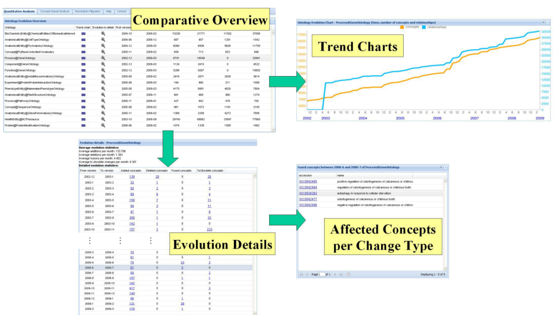
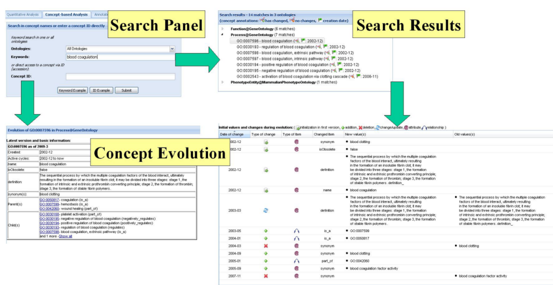


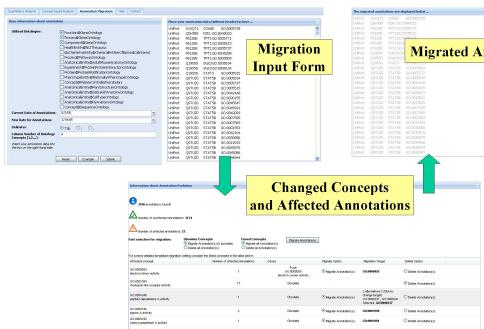
Fig. 25. Diff weighted Aggregate Taxonomy presented on the example of the Coronavirus Infectious disease ontology [29]



(a) Quantitative Evolution analysis workflow



(b) Concept-based analysis workflow



(c) Annotation migration workflow.

Fig. 26. ONEX visualisation of changes [8]

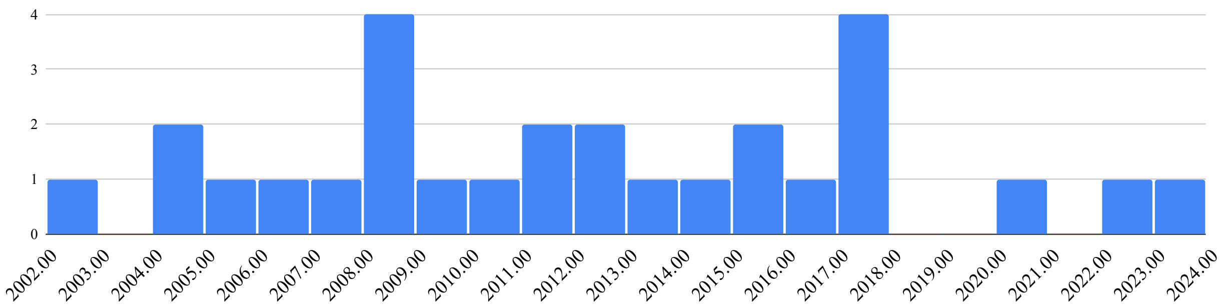


Fig. 27. Histogram of publication year.

do aspects of the found tools relate to the availability and publishing time of the tools? We address the four sub-research questions below in a subsection each after shortly discussing high-level trends regarding the publication years of the 28 tools.

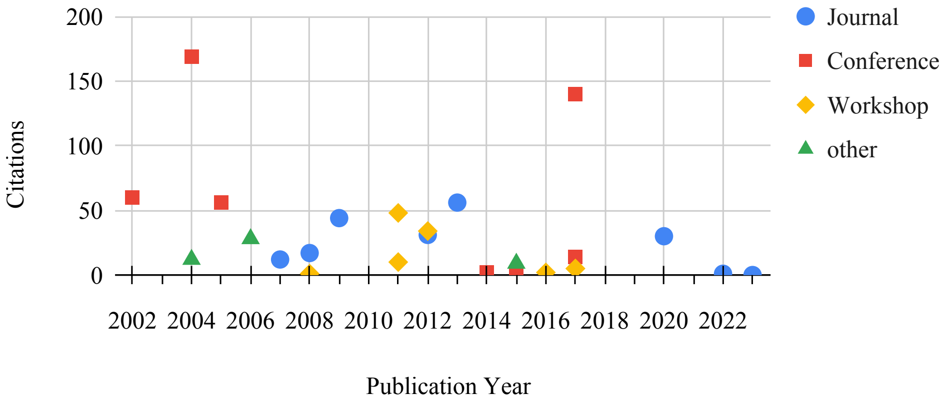
Figure 27 presents the histogram of the years of publication. This means that on the x-axis we see the year of publication of the tool, and on the y-axis the number of tools published in that particular year. We observe a steady publication of visualisation methods with a peak in both 2008 and 2017. However, since 2017, the visualisation of ontology changes and ontology evolution has not received much attention anymore.

5.1. Publication Venue

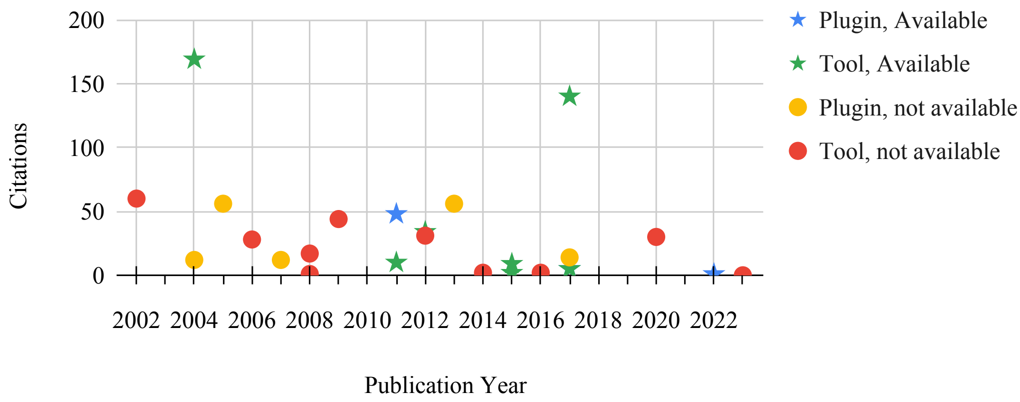
Figure 28 shows the publication year on the x-axis and the number of citations on the y-axis as a proxy for popularity to investigate the interaction between publication venue, year, popularity, and availability of the 25 methods associated with a publication. More specifically, Figure 28a indicates the type of publication: *journal* article, *conference*, *workshop* or *other* publication. We group thesis and demo publications in the *other* category for visualisation purposes. Figure 28b highlights the availability of tools and plugins, where the *availability* is signalled with a star and *no availability* with a circle. The colours further help distinguish between visualisation methods that are presented as plugins for Protégé [5] or NeOn [6], and standalone tools. Table 2 in Section 4 gives the detailed numbers (citations, publication year) together with the individual tool names to enable the mapping between the points in the figures and the individual methods.

The figures show two outliers that have received much more citations in comparison to all others: WIDOCO [36] and PromptDiff [44] which have around 150 citations each. All other tools and plugins have below 100 citations and 18 below 50 citations. We cannot see any clear trend between the different types of publications, but the two outliers are both conference publications. However, we think that the availability of these two tools plays just as important a role, since they are both still available to use today. Mapping the points between the two figures, we find that the other available tools and plugins seem to be mostly workshop or other publications, which begs why larger publications seem to lose or not have had any availability, except for the two outliers. One general hypothesis is that papers are presented at small venues when comparing conferences with workshops. However, journals then fall outside of this hypothesis because journal papers are not presented in front of an audience and, therefore, generally less visible. A similar argument could be made for those two outliers, given that they were presented at conferences and more people working with ontologies were made aware of them, which in turn could have led to them being spread more widely. Furthermore, because more people are interested in these two tools, this could have also had an impact on their popularity and availability. As long as there is interest in using these tools, there are volunteers who keep the code alive for use by themselves and others.

Taking a closer look at the two outliers: WIDOCO [36] and PromptDiff [44] are also of interest. Both published as parts of conference proceedings, they gained a substantially larger citation count than other tools. PromptDiff [44], published in 2004, is a particularly interesting case because the algorithm behind PrompDiff, which calculates the difference between two versions of ontologies has been integrated into Protégé fairly early, to facilitate collaborative editing. Although it was presented as a separate tool, it is no longer available as such but rather is completely



(a) Publication type



(b) Availability and plugin or tool

Fig. 28. Number of citations (y-axis) vs. publication year (x-axis), 3 tools excluded without associated publication.

integrated as a feature in Protégé [5] to date. Meaning that any user who uses Protégé has the implementation of PromtDiff inside Protégé, without even needing to install a plugin. Hence, the projection of this being a standalone tool is slightly misleading from today's point of view. Regarding WIDOCO [36], which was published in 2017, we believe that its availability is largely affected by its integration into LOT [49]. Therefore, similarly to PromtDiff, its inclusion in various projects[4] makes it a widely adapted tool.

Lastly, three tools were excluded from this analysis due to no associated publication. Due to missing associated publications, we were unable to include them in the figures. However, we want to address their accessibility, in particular. Two out of these three tools are still available today, published in 2008 and 2010 respectively. These tools are included in the subsequent questions, since we were able to extract the remaining analysis dimensions.

*Discussion of **RQ2.1:** Is tool popularity measured with citation count related to publication type, publishing time and availability?* We cannot identify any clear pattern between publication type, and popularity tools. Even though some observations can be made even if only indicative, given the small number of tools (28) and only two exceptional cases of impact. However, what we can see is that there is no difference between publishing tools in work-

[4]see success stories at https://lot.linkeddata.es/

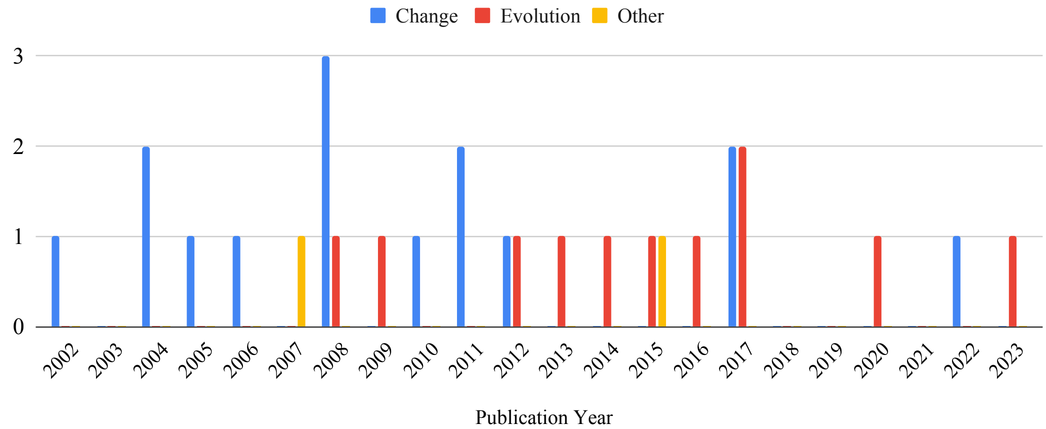


Fig. 29. Number of tools per year whose objective is either the visualisation of change, evolution or other.

shops, conferences, or journals. At least when citation count is taken into account, the venue does not seem to play as much of a role, as is often thought. The dissemination, adaption, or usage of the visualisation methods seems to indicate the possible availability of a tool years later.

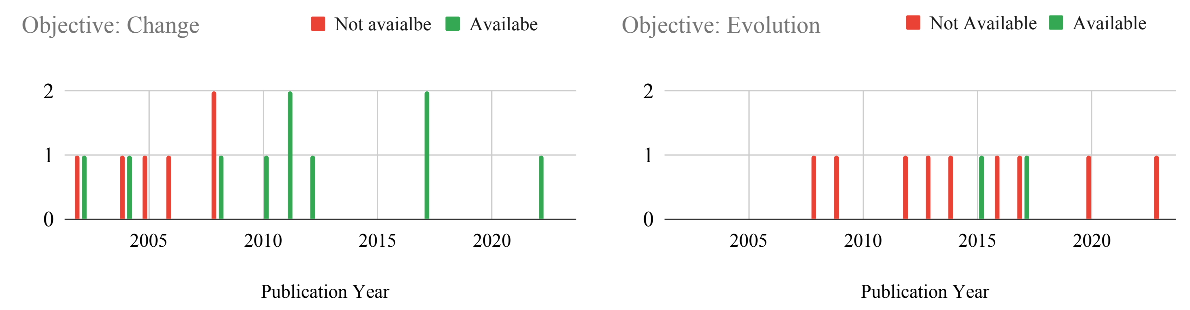
5.2. Visualisation Objective

Figure 29 showcases the different objectives of the tools: change, evolution, or other. We assign one objective to each tool, and we only identified two tools that have different objectives: Using text-mining [48], and AberOWL [40]. Using text-mining [48] objective is to measure and visualise concept clusters. This method can be used to visualise ontology changes and even evolution; however, the objective is to inform the user about the ontology itself and not its changes. AberOWL [40] is much closer to the objective of visualising changes and evolution; however, it goes a step further and also visualises the changes to the inference. Hence, the visualisation objective is on the change in inference rather than ontology changes or ontology evolution.

We see a shift in objective from communicating changes between ontologies to exploring and showcasing ontology evolution over time. Communicating ontology changes was the predominant objective in the early stages of the research field from 2002 until 2012. Only three more tools have been published since then, whose objective is communication and understanding of changes. The first tools focusing on evolution appeared in 2008 and 2009 but the research into evolution visualisation over from 2013 onward.

To further analyse this trend, we visually represent the two objectives (change and evolution visualisation) separately with regard to the availability of the tools presented in Figure 30. Figure 30a shows the tools that portray change as an objective and Figure 30b focusses on the tools whose objective is to communicate ontology evolution. We observe a clear difference between the two figures, mainly that only two of the evolution tools are available, while more than 50% of the change tools are still available. First, we need to take into account that in some cases, the implementation of the presented tool was never available and the publication only showcased a potential approach for visualisation. There are four such cases for the evolution visualisation objective (Change Tracer [11], HKG [13], Extending small seed ontology [38], DWAT [29]), two for the change visualisation objective (OntoAnalyzer [7], Colour-coded Layered Graph [37]) and one other objective (Using text-mining [48]). In some cases, there is no indication of the code in the publication. For tools showcasing evolution, this means that four out of eleven tools (36%) do not provide an implementation, while only two out of 15 tools (13%) were never implemented when it comes to the objective of visualising changes.

*Discussion on **RQ2.2:** Do the different tool objectives (visualisation of change, ontology evolution or other) relate to publishing time and their availability?* We can see a clear shift from the development of tools for ontology



(a) Objective change, available: 10, not available: 6, total: 16. (b) Objective evolution, available: 2, not available: 8, total: 10

Fig. 30. Objective of the tools in comparison to their availability. We excluded 2 tools with other visualisation objectives.

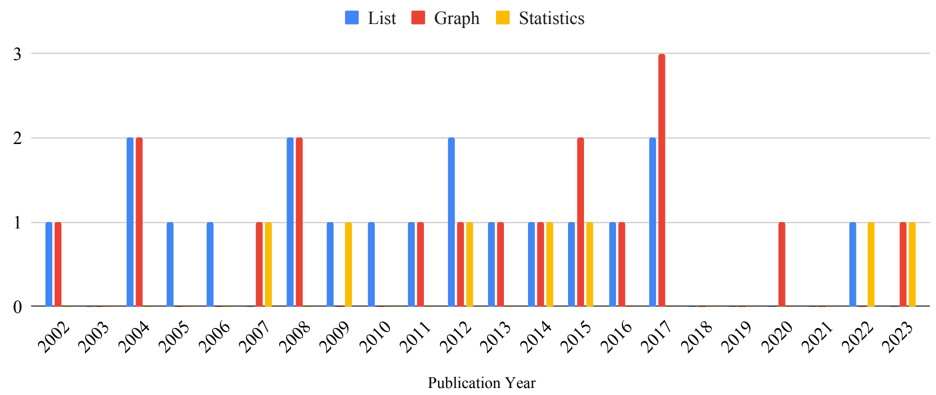


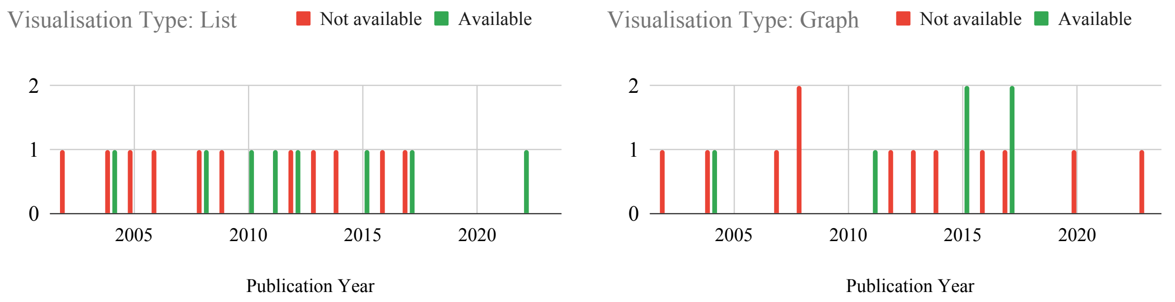
Fig. 31. Number of tools per year showcasing showing the type of visualisation: list, graph or statistics, some tools are counted multiple times as they have multiple visualisations.

change communication to ontology evolution throughout the years. Given that ontology change is the first step towards ontology evolution, this is not at all surprising. However, it should not be underestimated how important it is to be able to track, detect, and list individual changes. Depending on the ontology user, individual changes might be more important when the particular user is tasked with propagating changes to downstream applications [18]. Also, understanding the higher-level evolution of an ontology, especially when dealing with a large one, is just as important.

Relating the visualisation objective to the availability of the implementation of the proposed methods, we see a small trend with missing implementations when it comes to exploring ontology evolution. This can potentially be associated with the higher complexity of such an implementation. However, due to the high motivation of being able to learn about the evolution of an ontology when e.g. starting to work with a new ontology, we urge researchers not only to present approaches, but also to follow up their work with an implementation that can be used by the community. This is especially important for further research on understanding ontology evolution [50].

5.3. *Types of Visualisations*

Figure 31 showcases the different visualisation types, namely list, graph and statistics. In the figure, the tools do not add up to the total but exceed it, as 13 out of 28 tools make use of more than one way of visualising the change information. We excluded the category "other", due to the small number of tools (four), as well as these tools also having one of the other three types of visualisation present; hence, the tools themselves were not excluded from



(a) Visualisation type list, available: 8, not available: 11, total: 19.

(b) Visualisation type graph, available: 6, not available: 12, total: 18.

Fig. 32. Visualisation type compared to their availability.

the analysis, only the visualisation type. 19 tools integrate a list of changes within their functionalities. 17 methods use graph-like visualisations to showcase changes within an ontology. Seven approaches utilize statistics in their explanation or showcasing of changes within ontologies: CODEX [46], D2V [47], REX [12], ChImp [18], OnEX [8], Using text-mining [48] and DWAT [29] Including those statistics enhances the users' understanding of changes between two ontology versions. In the figure, we can see a slight trend toward graph visualisations; however, list visualisations have not necessarily decreased in popularity. The use of statistical information does not show any trend.

To investigate the interaction between the type of visualisation and availability, we visualised the dimensions in Figure 32. The two visualisation types, list and graph, are shown in separate figures, Figure 32a and Figure 32b, respectively. In both cases, more than 50% of the tools are not available, more specifically, list visualisation types are not available 58% and graph visualisation types 67%. However, we do not see any specific trend between availability type and publication year, except that graph visualisation types are more often not available.

*Discussion on **RQ2.3:** Do visualisation types of the presented tools relate to the time of publishing and their availability?* We identify a trend in using graph visualisations, as they became more used over the years. The usage of list visualisations seems to be persistent over the years. The usage of statistics has increased, but not many tools have made use of them so far. We found that tools that use graph visualisations are more often not available than list visualisations, but the difference is not large.

5.4. Interactiveness

Figure 33 shows that most tools are presented as interactive tools and only nine are static. Static in this context means that the user cannot interact with the visualisation; however, it does not mean that the visualisation does not update. For example, ChImp [18] is a static visualisation, since the user cannot drill down or explore more about the changes, but the visualisation updates as the user changes the ontology. Notable are the two spikes in 2008 and 2017, as discussed earlier. The difference between these two spikes is the interactiveness of the tools published at these times. In 2007 and 2008, all published tools were static, whereas from 2011 onwards until the peak in 2017, they were interactive. Only recently, from 2020 onwards, have new static tools been published. Therefore, there has always been a clear preference for interactive tools, as they provide a better experience for the user because the user can choose where they want to look deeper and know more about a change or evolution of the ontology.

We also look at the relation between interactiveness and availability of tools in Figure 34. Interactive tools, visualised in Figure 34a, show almost 50% availability (47%), while static tools have much lower availability (33%). However, there are far fewer static tools available than interactive ones. We can conclude that the complexity of implementing (and maintaining) an interactive tool in comparison to a static one does not seem to affect the availability of the tool.

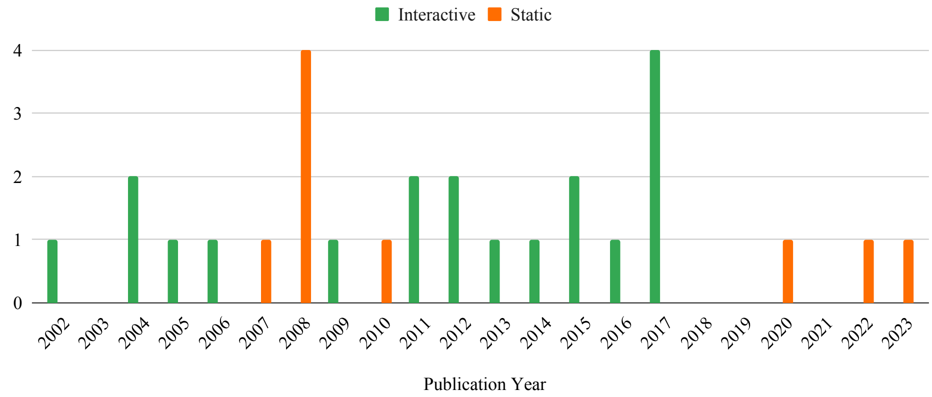
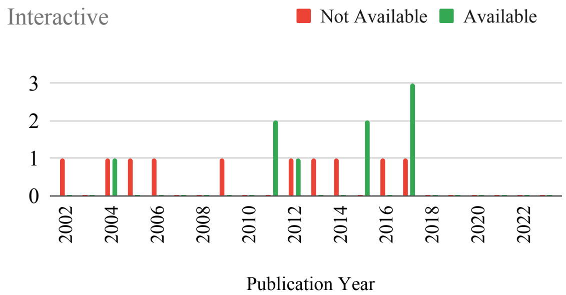
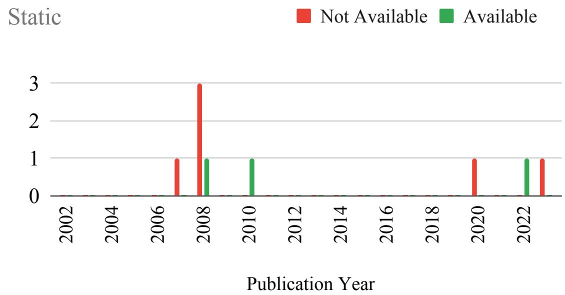


Fig. 33. Number of tools per year showcasing interactiveness of tools no multiple counts.



(a) Interactive tools, available: 9, not available: 10, total: 19.



(b) Static tools, available: 3, not available: 6, total: 9.

Fig. 34. Interactiveness of a tool compared to its availability.

Discussion on ***RQ2.4:*** Does the interactiveness of tools present a relationship to the time of publishing and their availability? It is notable that we found more interactive tools than static, however, since 2017 only three tools have been published, all static but mixing the form of change communication. We see the peak of research into visualising ontology changes in 2017, however, we think that a revival might be on the horizon. Given the frequent adaptation of ontologies in industry, visualisation tools will soon follow to allow non-experts and novices an easier entry into a field using ontologies [18]. We also found that the higher complexity required for an interactive tool does not seem to impact the availability of such tools in comparison to static ones.

5.5. Availability

Lastly, we want to discuss the availability of the tools presented. With availability, we refer to the A of the FAIR principles, namely accessibility. Instead, we use the term availability, as accessibility can refer to disability accommodations when discussing tools. We already addressed the availability of the tools with respect to other aspects: Figure 28b showcases the popularity of the tools in comparison to publication as well as if they are a plugin or standalone tool, Figure 30 captures the objective of the tools in comparison to their availability, Figure 32 shows the visualisation type and their associated availability, and lastly, Figure 34 indicates the availability of tools in comparison with their interactive and static nature.

Particularly interesting is that the two most cited tools are still available today. However, there are plenty of other tools that are still available with a low citation count, and we cannot confirm this trend. We found that the visualisation objective seems to play a role in the availability of the tools; however, we additionally also think that tools meant for evolution analysis are more often only presented conceptually and not implemented, or at least without indication of code in their publication. We did not find a difference in accessibility when considering the visualisation type, but the higher number of interactive tools does not seem to hinder availability.

What is most peculiar is that the age of a tool does not seem to be associated with its availability in any way. Though here we need to mention that we consider a tool to be available if we were able to locate their codebase but did not assess if the code is still executable. The mix of available and unavailable tools is throughout the whole 20 years comparatively the same.

*Discussion on **RQ2.5:** How is the accessibility of the tools from the perspective of FAIR principles affected by the different aspects of the tools like publishing time, association with an ontology editing environment, interactiveness, visualisation objective and visualisation type?* We investigated the different aspects also in other subquestions, but focus here purely on the availability of the tools. We do not see a trend with respect to the type or time of publication. However, the objective and interactiveness of the visualisation seem to play a role, but not the visualisation type. However, given the small number of tools 28 and even small numbers when slitting these into groups, we cannot statistically test our hypotheses and can only discuss the findings anecdotally.

6. Limitations and Future work

In any SLR, there are plenty of limitations and potential future work to be discussed. The SLR was conducted with Scopus as the search engine, but it is worth noting that this search engine may not include papers that, for example, Google Scholar would include. However, using Google Scholar provides additional challenges, as it is not a tool meant for the execution of SLRs per se, but as a search engine in general. Therefore, it does not prove the option of exporting results without significant (programming) efforts using their API. Additionally, the Google Scholar API has a retrieval limit of 100 results, which greatly hinders a smooth procedure.

Not only due to the time-consuming nature but also due to the lack of tool support, we did not execute a snowballing step in Round 2. This implies that we are potentially missing publication in this survey, but are nonetheless confident about its completeness, as we report not only on journal and conference publications which tend to be easier to locate but also on tools without applications and theses. With a tool to support the snowballing step, any SLR could benefit greatly.

It is important to note that this SLR did not encompass the visualisation of time-related aspects as we did not look into tools that allow for such information to be displayed. This paves the way for further research to explore the domain of temporal visualisation. The exploration could include researching tools that are capable of temporally visualising patterns or trends over time. This exploration will help users gain a deeper understanding of the evolution of data and knowledge, as required in [50].

Further research could involve user studies that investigate the usability, effectiveness, and user preferences of ontology change visualisation tools. This effort would be advantageous for users seeking the optimal tool for visualising ontology changes for their needs. Subsequently, additional research could focus on determining the best overall working technique for showcasing changes within ontologies. Gaining a clear understanding of the best working approach could prompt creators of ontology change visualisation tools to incorporate that technique, resulting in the development of enhanced ontology visualisation tools. As indicated by Chung et al. [19], there is no one tool that will fit all needs, but an investigation is extremely valuable to identify the best tools for certain needs.

Another potential avenue is the documentation of this SLR in an interactive website that would allow visitors to inform themselves about the different tools, their capabilities and drawbacks. Especially valuable would be a filtering function that lets the user find their way to a tool that would satisfy their needs.

7. Conclusion

Being able to learn about the past of an ontology is an important part of familiarising oneself with the domain of the ontology [50]. Visualisations are especially useful for novice users or non-experts [19, 51]. Previously, no

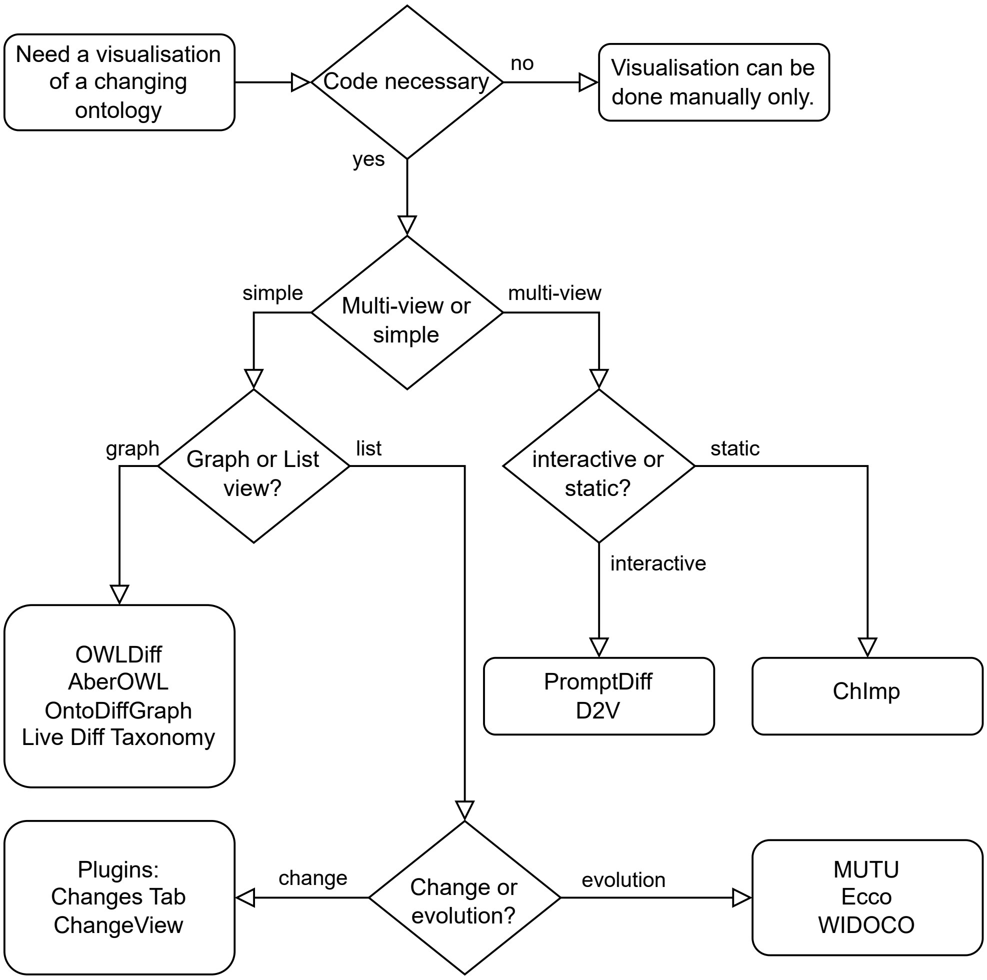


Fig. 35. Flowchart to help readers choose the most appropriate visualisation method according to the presented criteria.

comprehensive overview of ontology change visualisation approaches existed, which is the main contribution of this work. Therefore, we conducted an SLR on ontology change visualisation tools along with an analysis of the methodology used for that SLR. The SLR included collecting metadata that represents the change visualisation tools and investigating whether these tools were capable of showcasing ontology evolution.

The SLR resulted in the compilation of an overview of 28 tools and methods capable of visualising changes within ontologies. Of the 28 tools and methods, 12 tools are still available to use. The deeper analysis of the metadata that represents the ontology change visualisation tools shows that the following tools were especially good at showcasing ontology evolution: OntoAnalyzer [7], OnEX [8], EvoRDF [9], DIACHRON [10], Change Tracer [11], REX [12], and HGK [13]. Many of the 28 tools or methods include a graph-like visualisation (17 tools) and/or a list of changes (19 tools). The big spread of publication years of papers and the lack of a pattern in recent paper-linked tool availability show the ongoing process and evolving nature of ontology change visualisation tools.

The high-level SLR overview of the collected data on ontology change visualisation tools shows that a substantial amount of snowball tools (14) were included compared to Round 1 and 2 tools (13). The new search string caused three more snowball tools to be included in the results, but only one additional tool was approved using the inclusion and exclusion criteria. Even though we did not perform a second snowballing step, we are confident of our list of tools, as we were able to retrieve tools which do not have associated publications and also publications of small importance such as theses or demos. However, we urge researchers to focus on the snowballing part of the SLR methodology in the future and not underestimate its importance. In the future, we hope to see tools that could support researchers in this very time-consuming step of the process.

The SLR and analysis of the SLR methodology offer several implications for the domain of ontology change visualisation tools and SLR methodologies. Integrating TF-IDF statistics into the circular methodology approach could further enhance the accuracy and findability of more tools, as well as the construction of a good search string, especially if an initial list of seed publications is available. The overview of available ontology change visualisation tools presented in this paper serves as a valuable starting point, providing insights that can aid ontology engineers and users. Furthermore, this SLR can serve as a foundation for conducting user studies to identify the most suitable ontology change visualisation tools. This overview of ontology change visualisation tools can contribute to the refinement of both research practices and tool selection in the field of ontology change visualisation.

Appendix A. Appendix

As described in Section 4, we used TF-IDF measures to identify extra keywords for a second iteration of search. In this Appendix, we present in Figure 36 to summarise the findings.

References

[1] The Gene Ontology Consortium, The Gene Ontology Resource: 20 years and still GOing strong, *Nucleic Acids Research* **47**(D1) (2018), D330–D338. doi:10.1093/nar/gky1055.

[2] S. de Coronado, L. Remennik and P.L. Elkin, *National Cancer Institute Thesaurus (NCIt)*, in: *Terminology, Ontology and their Implementations*, P.L. Elkin, ed., Springer International Publishing, Cham, 2023, pp. 395–441. ISBN 978-3-031-11039-9. doi:10.1007/978-3-031-11039-9_17.

[3] E. Chang and J. Mostafa, The use of SNOMED CT, 2013-2020: a literature review, *Journal of the American Medical Informatics Association* **28**(9) (2021), 2017–2026. doi:10.1093/jamia/ocab084.

[4] R. Pernisch, D. Dell'Aglio and A. Bernstein, Beware of the hierarchy — An analysis of ontology evolution and the materialisation impact for biomedical ontologies, *Journal of Web Semantics* **70** (2021), 100658. doi:https://doi.org/10.1016/j.websem.2021.100658. https://www.sciencedirect.com/science/article/pii/S1570826821000330.

[5] M.A. Musen, The protégé project: a look back and a look forward, *AI Matters* **1**(4) (2015), 4–12. doi:10.1145/2757001.2757003.

[6] M. Erdmann and W. Waterfeld, *Overview of the NeOn Toolkit*, in: *Ontology Engineering in a Networked World*, M.C. Suárez-Figueroa, A. Gómez-Pérez, E. Motta and A. Gangemi, eds, Springer Berlin Heidelberg, Berlin, Heidelberg, 2012, pp. 281–301. ISBN 978-3-642-24794-1. doi:10.1007/978-3-642-24794-1_13.

[7] D. Rogozan and G. Paquette, Managing Ontology Changes on the Semantic Web, in: *2005 IEEE / WIC / ACM International Conference on Web Intelligence (WI 2005), 19-22 September 2005, Compiegne, France*, A. Skowron, R. Agrawal, M. Luck, T. Yamaguchi, P. Morizet-Mahoudeaux, J. Liu and N. Zhong, eds, IEEE Computer Society, 2005, pp. 430–433. doi:10.1109/WI.2005.92.

[8] M. Hartung, T. Kirsten, A. Groß and E. Rahm, OnEX: Exploring changes in life science ontologies, *BMC Bioinform.* **10** (2009). doi:10.1186/1471-2105-10-250.

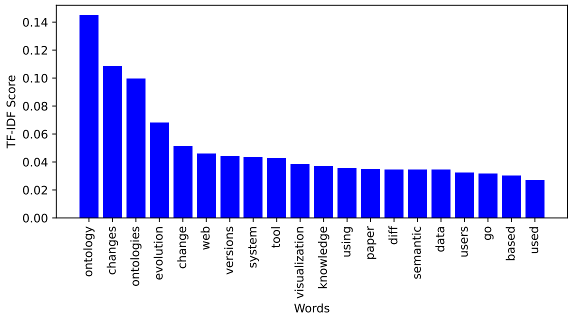
[9] H. Kondylakis, M. Despoina, G. Glykokokalos, E. Kalykakis, M. Karapiperakis, M. Lasithiotakis, J. Makridis, P. Moraitis, A. Panteri, M. Plevraki, A. Providakis, M. Skalidaki, A. Stefanos, M.G. Tampouratzis, E. Trivizakis, F. Zervakis, E. Zervouraki and N. Papadakis, EvoRDF: A Framework for Exploring Ontology Evolution, in: *The Semantic Web: ESWC 2017 Satellite Events - ESWC 2017 Satellite Events, Portorož, Slovenia, May 28 - June 1, 2017, Revised Selected Papers*, E. Blomqvist, K. Hose, H. Paulheim, A. Lawrynowicz, F. Ciravegna and O. Hartig, eds, Lecture Notes in Computer Science, Vol. 10577, Springer, 2017, pp. 104–108. doi:10.1007/978-3-319-70407-4_20.

[10] O. Vrousgou, T. Burdett, H.E. Parkinson and S. Jupp, Biomedical Ontology Evolution in the EMBL-EBI Ontology Lookup Service, in: *Proceedings of the Workshops of the EDBT/ICDT 2016 Joint Conference, EDBT/ICDT Workshops 2016, Bordeaux, France, March 15, 2016*, T. Palpanas and K. Stefanidis, eds, CEUR Workshop Proceedings, Vol. 1558, CEUR-WS.org, 2016. https://ceur-ws.org/Vol-1558/paper12.pdf.

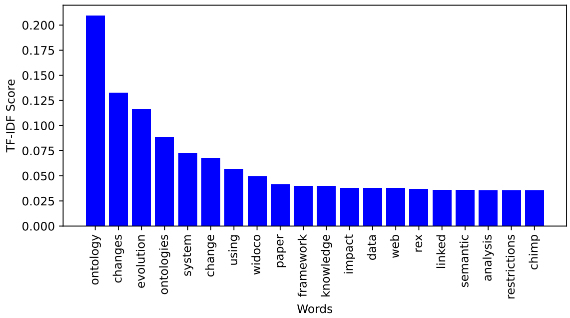
[11] A.M. Khattak, K. Latif and S. Lee, Change management in evolving web ontologies, *Knowl. Based Syst.* **37** (2013), 1–18. doi:10.1016/j.knosys.2012.05.005.

[12] V. Christen, A. Groß and M. Hartung, REX - A Tool for Discovering Evolution Trends in Ontology Regions, in: *Data Integration in the Life Sciences - 10th International Conference, DILS 2014, Lisbon, Portugal, July 17-18, 2014. Proceedings*, H. Galhardas and E. Rahm, eds, Lecture Notes in Computer Science, Vol. 8574, Springer, 2014, pp. 96–103. doi:10.1007/978-3-319-08590-6_9.

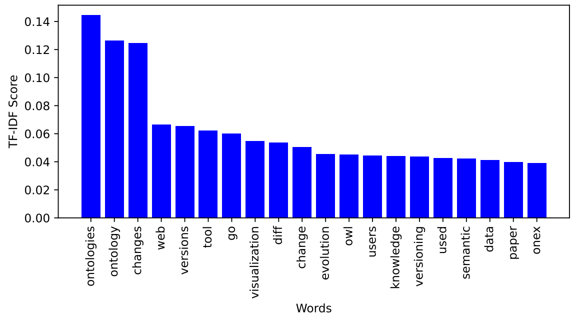
[13] S.D. Cardoso, M.D. Silveira and C. Pruski, Construction and exploitation of an historical knowledge graph to deal with the evolution of ontologies, *Knowledge Based Systems* **194** (2020), 105508. doi:10.1016/j.knosys.2020.105508.



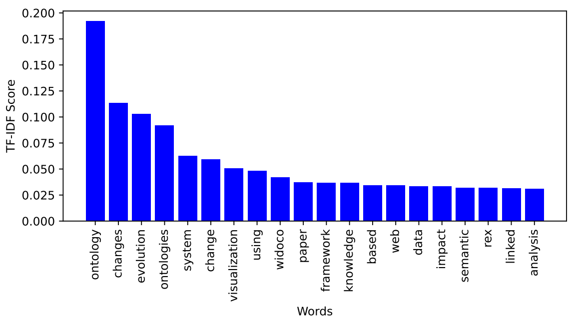
(a) TF-IDF for all selected tools.



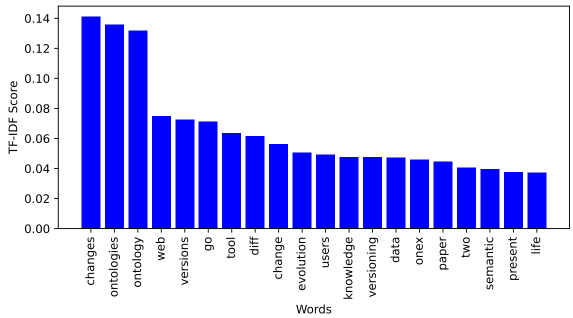
(b) TF-IDF for all selected tools in Round 1.



(c) TF-IDF for tools selected in snowballing during Round 1.



(d) TF-IDF for all selected tools in Round 2.



(e) TF-IDF for tools selected in snowballing during Round 2 (remaining tools not found in the Scopus search in Round 2).

Fig. 36. Figures showing the TF-IDF top 20 scoring words in title, abstract, and keywords for the selected tools at different stages.

[14] M. Martin, K. Abicht, C. Stadler, A.N. Ngomo, T. Soru and S. Auer, CubeViz: Exploration and Visualization of Statistical Linked Data, in: *Proceedings of the 24th International Conference on World Wide Web Companion, WWW 2015, Florence, Italy, May 18-22, 2015 - Companion Volume*, A. Gangemi, S. Leonardi and A. Panconesi, eds, ACM, 2015, pp. 219–222. doi:10.1145/2740908.2742848.

[15] A.M. Khattak, R. Batool, Z. Pervez, A.M. Khan and S. Lee, Ontology Evolution and Challenges, *J. Inf. Sci. Eng.* **29**(5) (2013), 851–871. http://www.iis.sinica.edu.tw/page/jise/2013/201309_04.html.

[16] M. Dudás, S. Lohmann, V. Svátek and D. Pavlov, Ontology visualization methods and tools: a survey of the state of the art, *Knowl. Eng. Rev.* **33** (2018), e10. doi:10.1017/S0269888918000073.

[17] R. Pernischová, M. Serbak, D. Dell'Aglio and A. Bernstein, ChImp: Visualizing Ontology Changes and their Impact in Protégé, in: *Proceedings of the Fifth International Workshop on Visualization and Interaction for Ontologies and Linked Data co-located with the 19th International Semantic Web Conference (ISWC 2020), Virtual Conference (originally planned in Athens, Greece), November 02, 2020*, V. Ivanova, P. Lambrix, C. Pesquita and V. Wiens, eds, CEUR Workshop Proceedings, Vol. 2778, CEUR-WS.org, 2020, pp. 47–60. https://ceur-ws.org/Vol-2778/paper5.pdf.

[18] R. Pernisch, D. Dell'Aglio, M. Serbak, R.S. Gonçalves and A. Bernstein, Visualising the effects of ontology changes and studying their understanding with ChImp, *Journal of Web Semantics* **74** (2022), 100715. doi:10.1016/j.websem.2022.100715. https://www.sciencedirect.com/science/article/pii/S1570826822000117.

[19] K. Chung, R. Pernisch and S. Schlobach, Descriptive Comparison of Visual Ontology Change Summarisation Methods, in: *The Semantic Web: ESWC 2023 Satellite Events*, Springer Nature Switzerland, Cham, 2023, pp. 54–58. ISBN 978-3-031-43458-7. doi:10.1007/978-3-031-43458-7_10.

[20] S. Ramakrishnan and A. Vijayan, A study on development of cognitive support features in recent ontology visualization tools, *Artif. Intell. Rev.* **41**(4) (2014), 595–623. doi:10.1007/s10462-012-9326-2.

[21] A. Katifori, C. Halatsis, G. Lepouras, C. Vassilakis and E.G. Giannopoulou, Ontology visualization methods - a survey, *ACM Comput. Surv.* **39**(4) (2007), 10. doi:10.1145/1287620.1287621.

[22] P. Haase and L. Stojanovic, Consistent Evolution of OWL Ontologies, in: *The Semantic Web: Research and Applications, Second European Semantic Web Conference, ESWC 2005, Heraklion, Crete, Greece, May 29 - June 1, 2005, Proceedings*, A. Gómez-Pérez and J. Euzenat, eds, Lecture Notes in Computer Science, Vol. 3532, Springer, 2005, pp. 182–197. doi:10.1007/11431053_13.

[23] G. Flouris, D. Manakanatas, H. Kondylakis, D. Plexousakis and G. Antoniou, Ontology change: classification and survey, *Knowl. Eng. Rev.* **23**(2) (2008), 117–152. doi:10.1017/S0269888908001367.

[24] F. Zablith, G. Antoniou, M. d'Aquin, G. Flouris, H. Kondylakis, E. Motta, D. Plexousakis and M. Sabou, Ontology evolution: a process-centric survey, *Knowl. Eng. Rev.* **30**(1) (2015), 45–75. doi:10.1017/S0269888913000349.

[25] P. Lambrix, Z. Dragisic, V. Ivanova and C. Anslow, Visualization for Ontology Evolution, in: *Proceedings of the Second International Workshop on Visualization and Interaction for Ontologies and Linked Data co-located with the 15th International Semantic Web Conference, VOILA@ISWC 2016, Kobe, Japan, October 17, 2016*, V. Ivanova, P. Lambrix, S. Lohmann and C. Pesquita, eds, CEUR Workshop Proceedings, Vol. 1704, CEUR-WS.org, 2016, pp. 54–67. https://ceur-ws.org/Vol-1704/paper5.pdf.

[26] B. Kitchenham and S. Charters, Guidelines for performing Systematic Literature Reviews in Software Engineering, Technical Report, Keele University and University of Durham, 2007.

[27] T. Dyba, T. Dingsoyr and G.K. Hanssen, Applying Systematic Reviews to Diverse Study Types: An Experience Report, in: *First International Symposium on Empirical Software Engineering and Measurement (ESEM 2007)*, 2007, pp. 225–234. doi:10.1109/ESEM.2007.59.

[28] G.A. Lewis, Software Architecture Strategies for Cyber-Foraging Systems, PhD thesis, Vrije Universiteit Amsterdam, 2016.

[29] L. Zheng, Y. Perl and Y. He, Big knowledge visualization of the COVID-19 CIDO ontology evolution, *BMC Medical Informatics and Decision Making* **23**(1) (2023), 88. doi:10.1186/s12911-023-02184-6.

[30] P. Plessers, An Approach to Web-based Ontology Evolution | WISE Lab, PhD thesis, Vrije Universiteit Brussel, 2006. https://wise.vub.ac.be/thesis/approach-web-based-ontology-evolution.

[31] W. Liu, T. Tudorache and T. Redmond, Changes Tab - Protege Wiki, 2008. https://protegewiki.stanford.edu/wiki/Changes_Tab.

[32] R. Palma, 1.x/Change Capturing - NeOn Wiki. http://neon-toolkit.org/wiki/1.x/Change_Capturing.html#How_to_use_it.

[33] N. Drummond and T. Redmond, Change View - Protege Wiki, 2010. https://protegewiki.stanford.edu/wiki/Change_View.

[34] S. Pessala, K. Seppala, O. Suominen, M. Frosterus, J. Tuominen and E. Hyvonen, MUTU: An Analysis Tool for Maintaining a System of Hierarchically Linked Ontologies, in: *Proceedings of the ISWC 2011 Workshop Ontologies Come of Age in the Semantic Web (OCAS)*, 2011.

[35] R.S. Gonçalves, B. Parsia and U. Sattler, Ecco: A Hybrid Diff Tool for OWL 2 ontologies, in: *Proceedings of OWL: Experiences and Directions Workshop 2012, Heraklion, Crete, Greece, May 27-28, 2012*, P. Klinov and M. Horridge, eds, CEUR Workshop Proceedings, Vol. 849, CEUR-WS.org, 2012. https://ceur-ws.org/Vol-849/paper_27.pdf.

[36] D. Garijo, WIDOCO: A Wizard for Documenting Ontologies, in: *The Semantic Web - ISWC 2017 - 16th International Semantic Web Conference, Vienna, Austria, October 21-25, 2017, Proceedings, Part II*, C. d'Amato, M. Fernández, V.A.M. Tamma, F. Lécué, P. Cudré-Mauroux, J.F. Sequeda, C. Lange and J. Heflin, eds, Lecture Notes in Computer Science, Vol. 10588, Springer, 2017, pp. 94–102. doi:10.1007/978-3-319-68204-4_9.

[37] J.C. Park, T. Kim and J. Park, Monitoring the evolutionary aspect of the Gene Ontology to enhance predictability and usability, *BMC Bioinform.* **9**(S-3) (2008). doi:10.1186/1471-2105-9-S3-S7.

[38] A. Weichselbraun, A. Scharl and W. Liu, Capturing and Classifying Ontology Evolution in News Media Archives, in: *19th International Workshop on Database and Expert Systems Applications (DEXA 2008), 1-5 September 2008, Turin, Italy*, IEEE Computer Society, 2008, pp. 197–201. doi:10.1109/DEXA.2008.126.

[39] P. Kremen, M. Smid and Z. Kouba, OWLDiff: A Practical Tool for Comparison and Merge of OWL Ontologies, in: *2011 22nd International Workshop on Database and Expert Systems Applications*, 2011, pp. 229–233. doi:10.1109/DEXA.2011.62.

[40] M.Á. Rodríguez-García, L.T. Slater, K. O'Shea, P.N. Schofield, G.V. Gkoutos and R. Hoehndorf, Visualising Ontologies with AberOWL, in: *Proceedings of the 8th Semantic Web Applications and Tools for Life Sciences International Conference, Cambridge UK, December 7-10, 2015*, J. Malone, R. Stevens, K. Forsberg and A. Splendiani, eds, CEUR Workshop Proceedings, Vol. 1546, CEUR-WS.org, 2015, pp. 183–192. https://ceur-ws.org/Vol-1546/poster_33.pdf.

[41] A. Lara, P.R. Henriques and A.L. Gançarski, Visualization of Ontology Evolution using OntoDiffGraph, in: *6th Symposium on Languages, Applications and Technologies, SLATE 2017, June 26-27, 2017, Vila do Conde, Portugal*, R. Queirós, M. Pinto, A. Simões, J.P. Leal and M.J.V. Pereira, eds, OASIcs, Vol. 56, Schloss Dagstuhl - Leibniz-Zentrum für Informatik, 2017, pp. 14:1–14:8. doi:10.4230/OASIcs.SLATE.2017.14.

[42] C. Ochs, J. Geller, M.A. Musen and Y. Perl, Real Time Summarization and Visualization of Ontology Change in Protégé, in: *Proceedings of the Third International Workshop on Visualization and Interaction for Ontologies and Linked Data co-located with the 16th International Semantic Web Conference (ISWC 2017), Vienna, Austria, October 22, 2017*, V. Ivanova, P. Lambrix, S. Lohmann and C. Pesquita, eds, CEUR Workshop Proceedings, Vol. 1947, CEUR-WS.org, 2017, pp. 75–86. https://ceur-ws.org/Vol-1947/paper07.pdf.

[43] M.C.A. Klein, A. Kiryakov, D. Ognyanov and D. Fensel, Finding and Characterizing Changes in Ontologies, in: *Conceptual Modeling - ER 2002, 21st International Conference on Conceptual Modeling, Tampere, Finland, October 7-11, 2002, Proceedings*, S. Spaccapietra, S.T. March and Y. Kambayashi, eds, Lecture Notes in Computer Science, Vol. 2503, Springer, 2002, pp. 79–89. doi:10.1007/3-540-45816-6_16.

[44] N.F. Noy, S. Kunnatur, M.C.A. Klein and M.A. Musen, Tracking Changes During Ontology Evolution, in: *The Semantic Web - ISWC 2004: Third International Semantic Web Conference,Hiroshima, Japan, November 7-11, 2004. Proceedings*, S.A. McIlraith, D. Plexousakis and F. van Harmelen, eds, Lecture Notes in Computer Science, Vol. 3298, Springer, 2004, pp. 259–273. doi:10.1007/978-3-540-30475-3_19.

[45] J. Wu, J.J.Y. Chung and E. Adar, viz2viz: Prompt-driven stylized visualization generation using a diffusion model, *CoRR* **abs/2304.01919** (2023). doi:10.48550/arXiv.2304.01919.

[46] M. Hartung, A. Groß and E. Rahm, CODEX: exploration of semantic changes between ontology versions, *Bioinformatics* **28**(6) (2012), 895–896. doi:10.1093/bioinformatics/bts029.

[47] Y. Roussakis, I. Chrysakis, K. Stefanidis and G. Flouris, D2V: A Tool for Defining, Detecting and Visualizing Changes on the Data Web, in: *Proceedings of the ISWC 2015 Posters & Demonstrations Track co-located with the 14th International Semantic Web Conference (ISWC-2015), Bethlehem, PA, USA, October 11, 2015*, S. Villata, J.Z. Pan and M. Dragoni, eds, CEUR Workshop Proceedings, Vol. 1486, CEUR-WS.org, 2015. https://ceur-ws.org/Vol-1486/paper_26.pdf.

[48] M. Enkhsaikhan, W. Wong, W. Liu and M. Reynolds, Measuring Data-Driven Ontology Changes using Text Mining, in: *Data Mining and Analytics 2007, Proceedings of the Sixth Australasian Data Mining Conference (AusDM 2007), Gold Coast, Queensland, Australia, December 3-4, 2007, Proceedings*, P. Christen, P.J. Kennedy, J. Li, I. Kolyshkina and G.J. Williams, eds, CRPIT, Vol. 70, Australian Computer Society, 2007, pp. 39–46. http://crpit.scem.westernsydney.edu.au/abstracts/CRPITV70Enkhsaikhan.html.

[49] M. Poveda-Villalón, A. Fernández-Izquierdo, M. Fernández-López and R. García-Castro, LOT: An industrial oriented ontology engineering framework, *Engineering Applications of Artificial Intelligence* **111** (2022), 104755. doi:https://doi.org/10.1016/j.engappai.2022.104755.

[50] A. Polleres, R. Pernisch, A. Bonifati, D. Dell'Aglio, D. Dobriy, S. Dumbrava, L. Etcheverry, N. Ferranti, K. Hose, E. Jiménez-Ruiz, M. Lissandrini, A. Scherp, R. Tommasini and J. Wachs, How Does Knowledge Evolve in Open Knowledge Graphs?, *Transactions on Graph Data and Knowledge* **1**(1) (2023), 11:1–11:59. doi:10.4230/TGDK.1.1.11.

[51] A. Pereira, J.R. Almeida, R.P. Lopes and J.L. Oliveira, Visualising Time-evolving Semantic Biomedical Data, in: *35th IEEE International Symposium on Computer-Based Medical Systems, CBMS 2022, Shenzen, China, July 21-23, 2022*, L. Shen, A.R. González, K. Santosh, Z. Lai, R. Sicilia, J.R. Almeida and B. Kane, eds, IEEE, 2022, pp. 264–269. doi:10.1109/CBMS55023.2022.00053.