Utilising KGs for Comprehensive Carbon Reduction Assessment

Full research paper

Abstract

Carbon reduction activities heavily rely on the ability to access, integrate, and reason over diverse emission reduction datasets, which are isolated and fragmented across different organizations. In this paper we present CRA (Carbon Reduction Assessment) Framework, an ontology-based framework for carbon reduction assessment (CRA framework) and associated knowledge graph. This work builds on our preliminary research <removed for refereeing>, and addresses key challenges identified through the proof-of-concept evaluation improved domain coverage, access by non-IT specialists for decision support, and overcoming limited quantity of data sources. We present an elaborate ontology that capture the complexity of the carbon credit ecosystem, and a knowledge graph based on the ontology that interfaced to variety of external data sources, enabling more refined queries and better semantic coverage. We evaluate the CRA framework to assess its ease of use, coverage, consistency, and accuracy, overall providing strong evidence that the CRA framework in this paper offers promising capabilities in data integration, advanced reasoning, and associated decision-making process.

Keywords: Carbon Reduction Assessment, Ontology, Knowledge Graph, Climate Change, SPARQL

1 Introduction

Global communities are thinking of an effective way to mitigate climate change by reducing carbon emissions. Different countries and organizations are working together to formulate initiatives like the United Nations Framework Convention on Climate Change (UNFCCC), Intergovernmental Panel on Climate Change (IPCC), etc., for effectively reducing the carbon emissions (King 2004; VijayaVenkataRaman et al. 2012). The use of renewable energy, Carbon sequestration, Clean Development Mechanisms, and Joint implementation are considered as the most important measures for carbon emission reduction (United Nations Climate Change 2022; VijayaVenkataRaman et al. 2012). Assessing, tracking, and managing carbon reduction strategies requires a robust framework. This requires accounting for CO2 emissions irrespective of their origin (United Nations Climate Change 2022) and bringing together a multitude of different stakeholders and players with overlapping roles. These include Carbon reduction project developers, Carbon credit registries and standard bodies, Carbon credit verifiers, Carbon credit brokers and marketplace, Carbon credit ratings agencies and possibly others (Walsh and Toffel 2023). Knowledge management frameworks have the potential to assist in this endeavour acting as data and knowledge sharing platform that can cater different needs of stakeholders. Such implementation in other domains has proven invaluable in structuring and modeling knowledge, providing semantic clarity, and enabling automated reasoning (Cui et al. 2025; Wan et al. 2024; Wang et al. 2024).

Our previous work <removed for refereeing> proposed the preliminary design of the ontology-based framework for carbon reduction assessment (CRA framework), facilitating structured knowledge representation, improved decision-making, and addressing challenges faced by stakeholders in carbon reduction projects. Through a proof of concept <removed for refereeing>, we identified further challenges to realise such an operational framework including a reliable domain coverage, easy-to-use decision-support capabilities and compensating for incomplete data sources. This paper presents the refined and comprehensive CRA framework addressing these challenges, incorporating more reliable and diverse data, and providing a novel approach for data-driven decision-making capabilities. We incorporate industry standard techniques for ontology and knowledge graph revision to enhance the initial CRA framework. The central ontology is updated to represent comprehensive concepts, properties, and relationships that capture the complexity of the carbon credit ecosystem. Moreover, this ontology has the ability to be refined by improving the nomenclature of the vocabulary used in the ontology so that it maintains consistency over different carbon credit registries. Our key contributions are:

- Comprehensive ontology for carbon reduction assessment knowledge representation that updates in real time to reflect changes in the ecosystem
- Knowledge graph based on the ontology accumulating variety of data sources
- A system architecture that utilizes ontology and knowledge graph to enable decision support and ease of use for non-technical users
- Comprehensive evaluation of CRA framework based on industry use cases

The rest of the paper is organized as follows: Section 2 is related work on the field of ontology and knowledge graph, followed by Methodology (Section 3), providing details on how we applied the Design Science Research (DSR) Methodology for iterative development. Section 4 is about the CRA framework, which explains the design and development phase of the CRA framework in detail. Section 5 contains the demonstration and evaluation of the CRA framework followed by results and discussion in section 6, and conclusion in section 7.

2 Background

Recently, the advancement in Natural Language Processing and Generative AI based analysis demands high quality knowledge base, leading to research taking place in the domain of the Knowledge Graph. There are Generic Knowledge Graphs such as DBPedia[1], Wikidata[2], YAGO[3], and Domain-specific Knowledge Graph focusing on a particular field, such as education, medicine, finance, and environment (Abu-Salih 2021; Lin et al. 2021; Zou 2020). Ontologies serve as the foundational tools in knowledge-

[1] https://www.dbpedia.org/
[2] https://www.wikidata.org/
[3] https://yago-knowledge.org/

based systems, enabling shared understanding, semantic interoperability, and logical reasoning. In the scope of this project, we adopt the classic definition of an ontology as an explicit specification of a conceptualization (Gruber 1993) that represents the description of the concepts and the relationship between the concepts within the domain. A KG can be created integrating a suite of ontologies (Akroyd et al. 2021; Hogan et al. 2021) enabling new knowledge discovery through interlinks and inference. Graph data models, such as RDF, are commonly used for encoding the knowledge graph, and support semantic querying (e.g., SPARQL), reasoning, integrating heterogeneous datasets, and visual exploration of complex information (Ali et al. 2022).

Many researchers' proposing domain-specific knowledge graphs present them assuming the domain knowledge is static and does not support for knowledge updated over time. Yet in real world, not only data, but the schema-level (ontology) also should be updated and maintained over time (Stojanovic 2004) and only few studies investigate this challenge (Polleres et al. 2023). Key challenge in ontology evolution is how we detect the need for evolution. Different criteria and properties are used to evaluate the ontology such as ontology and data coverage, the specific use case scenarios, consistency, query coverage(Grüninger and Fox 1995; Noy and McGuinness 2001), Stakeholders' needs, and completeness of the ontology (Obrst et al. 2007).

Carbon Credit Ecosystem, where greenhouse gases (GHG) are traded in terms of carbon credit seems to have great potential for reducing GHG from the atmosphere (Kukah et al. 2025). But managing, tracking, and verifying the carbon reduction assessment (CRA) in the carbon credit ecosystem is complicated due to challenges associated with the data integration from multiple sources and challenges associated with the environmental integrity(Mehling 2009). Moreover, the global carbon credit ecosystem is fragmented between different countries, or organizations. Linking the fragmented bodies, that have been performing independently with their own set of standard and processes is complicated task (Newell et al. 2013). Our previous paper <removed for refereeing>, had shown great potential of ontology to model the existing carbon credit ecosystem as concepts and link them with certain relationships. Populating the existing data sources from the multiple registries along with the ontology had incredibly helped linking the multiple registries and had shown the potential of KG and ontology in managing, integrating, tracking, and verifying the carbon reduction assessment in the domain of carbon credit ecosystem.

3 Research Method

We follow the Design Science Research Methodology (DSRM) process model outlined in (Peffers et al. 2007) for developing, demonstrating, and evaluating the Carbon Reduction Assessment (CRA) framework. DSRM provides a structured approach to solving real-world problems by creating innovative artifacts (Hevner 2007; March and Smith 1995). The DSRM process model has six distinct phases, which are outlined in Figure 3.1.

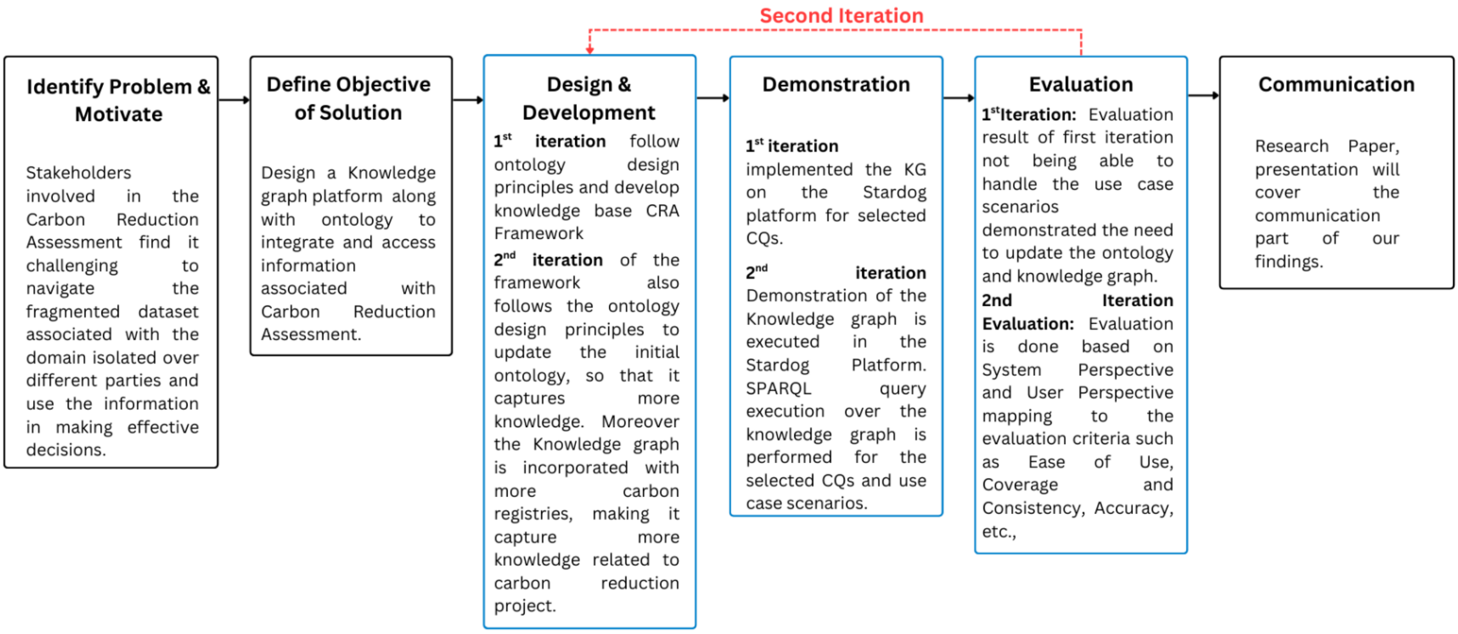

Figure 3.1 Adapted steps of the DSR Process model from (Peffers et al., 2007) to conduct research for developing the CRA Framework. This figure illustrates the second iteration of the DSRM.

In the first phase, "Identify problem & motivate", we identified different stakeholder and their challenges in implementing carbon reduction projects. These include: the carbon reduction project developer, the project manager, carbon credit buyers and offsetting organizations, and investors and financial institutions. The dynamic nature of carbon credits themselves is also accommodated. That is, the representation of the Carbon Credit (Retired/Remaining) is captured, making it easier to represent, understand, manage, and analyze the carbon credit data available from different registries.

The second phase, "Define the Objective of a Solution", the IS artifact sought is the carbon semantic-based carbon reduction assessment framework. Key criteria for our CRA framework, are coverage and consistency of the domain, and ease of use. The coverage and consistency criteria suggest the expansion and refinement of the existing ontology to a new one that covers more domain knowledge. Ease of use evaluation criteria suggest that non-technical users are facing difficulties in writing the SPARQL queries themselves, which leads to the objective of Natural Language Query to our Knowledge Base. This suggests use of Large Language Model (LLM) for generation SPARQL queries (LLM integration is not covered by this paper).

In the third phase, "Design and Development", our work relies more on already existing data from different carbon registries. Constructing an ontology model will define a common vocabulary to enable structured and domain-based communication between the stakeholders and the operationalised framework. The ontology will also form the basis for representing relevant knowledge within the operationalisation (i.e., the system). A proof of concept of the CRA framework (outcome of DSR iteration 1) that demonstrated the feasibility of a domain-specific knowledge graph developed on top of the CRA ontology was proposed in our earlier paper <removed for refereeing>. That study was evaluated using the Competency Questions (CQs) and demonstrated the knowledge graph's capability in managing fragmented emission reduction project data. However, through that evaluation we also discovered following challenges:

1. The CRA ontology did not cover a wider range of concepts and the ontology from first iteration had missing relationships and properties as well. For example, if we consider a use case scenario of "Environmental Impact Assessment", where stakeholders like carbon market developers and project managers, or carbon credit buyers are interested in identifying certain climatic features associated with the projects. In this case, the previous version lacks representation of the relationships between the project and the climatic features associated with the project location, suggesting there is a need for an update in the ontology.

2. The knowledge graph did not capture the data from all the carbon registries. The first paper theoretically explained that the CRA framework can handle the fragmented data sources among the multiple carbon registries. But it was demonstrated for capturing the data from only one carbon registry.

3. The concepts and the relationships between the concepts are shown using the ID in the knowledge graph, which caused difficulty in navigating and querying the knowledge graph.

In response to these identified challenges from the first iteration, this paper presents the second iteration of the DSRM process model, addressing all the challenges of the CRA framework identified in the first iteration. The beauty of the DSRM process model is that the research is classified and structured into six distinct phases, with the process iteration features. There is the flexibility to jump back either to "Define Objective of a Solution" or "Design and Development" phase based on findings and needs of the iteration. The second iteration of the CRA framework focuses on iterative ontology and knowledge graph refinement, which emphasizes the continuous "Design and Development" and "Evaluation" phases of the DSRM process model that have led to the framework's current state.

The design and development phase of the DSRM process model highlights the iterative advancements in core artifact development: the CRA framework, focusing on the development of CRA ontology and knowledge graph. The ongoing iterative cycle of this phase has been driven by the expanded data requirements, continuous evaluation, and validation of the CRA framework against the real-world scenarios. During the evolution and enhancement process, we first analyzed the emission reduction project data from four different carbon registries and associated data sources related to this domain. Different data sources have been considered while obtaining the metadata to model the ontology.

Appendix A, Table A1 presents an overview of the data sources used to create the knowledge graph representing the CRA framework.

In the fourth phase, "Demonstration", we implement this ontology in the cloud-based Stardog enterprise knowledge graph platform. This follows the RDF/OWL notation and semantic web standards.

For evaluating the knowledge graph, we developed a set of competency questions (CQs) that captured the information needs of the different stakeholders and used the SPARQL query to query the knowledge graph and observe the capability of the knowledge graph to answer the competency questions. Moreover, two different use case scenarios: "Ranking Project Developer" and "Environmental Impact Assessment" are used to evaluate the KG. In second iteration, the evaluation is performed as system perspective and user perspective. The demonstration and evaluation are detailed in section 5. The results of "Evaluation" will be used to inform the iterations over phases 3 and 4. This will serve to resolve any labelling or semantic inconsistencies so that data from the different registries can be linked within our knowledge graph. It will also ensure that the various queries of stakeholders are adequately met.

Research paper and research presentation are used to communicate our proposed approach and findings, completing the last step of the DSR process.

4 CRA Framework

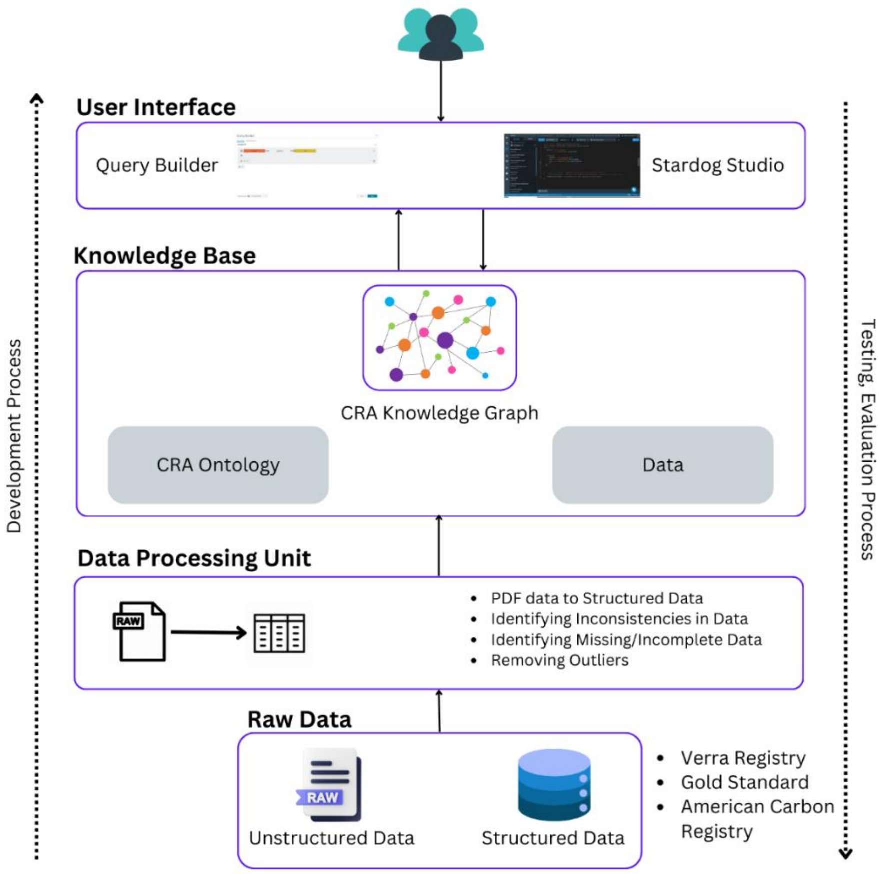

Figure 4.1 Schematic Representation of CRA Framework, including the data pipeline for populating and querying the proposed <removed for refereeing>

The architectural overview of the CRA framework is shown in Figure 4.1. This architecture was presented in the Design and Development phase of the DSRM process model in the first iteration. It consists of four different layers: Raw Data, Data Processing Unit, Knowledge Base, and User Interface. The identified raw data description is given in Appendix A, Table A1. Inconsistencies, duplicates, and incomplete data are identified in the data processing unit. This data preprocessing task is accomplished using the Python programming language. Knowledge base is the core component of this architecture, consisting of the CRA ontology and CRA Knowledge Graph, which are explained in detail in sections 4.1 and 4.2, respectively. Finally, the last layer of the architecture is the User Interface, providing the stakeholders with an interactive way to interact with the carbon credit ecosystem. User interactions with the knowledge base can be performed in two different ways: using query builder features of Stardog or through SPARQL (which is the standard query language for the Semantic Web).

4.1 Ontology Modelling

In the first iteration, CRA ontology included 14 different concepts along with their properties and relationships between the concepts. This paper presents the second iteration of the DSRM process model, which enhanced the ontology from the first iteration.

Figure 4.2 shows the visualization of the changes in the ontology from the first iteration to the second iteration. The circle in the ontology diagram represents the concepts (also called classes), the arrow shows relationships between the concepts, and the properties related to each concept are shown in the rectangular box attached to the concepts. Appendix A, Table A2 shows the finalised concept catalogue of CRA ontology. Also note that some of the concept's naming conventions had been updated from the earlier version, so that the ontology will be more dependable and consistent across all the carbon credit registries.

A key enhancement in the CRA ontology is the inclusion of the two main concepts, which are "Greenhouse Gas Emission" and "Location Specific Feature". Including "Greenhouse Gas Emission" enables in-depth analysis of the emissions produced by any country and how the emission reduction projects developed in that country can reduce these emissions. Similarly, including "Location Specific Features" provides stakeholders the capability to compare associated climatic features with already built projects and get insights on selecting the proper methodology for developing the new project. It increases the efficiency of the project development process, by reducing the time spent on finding methodologies to develop a new project.

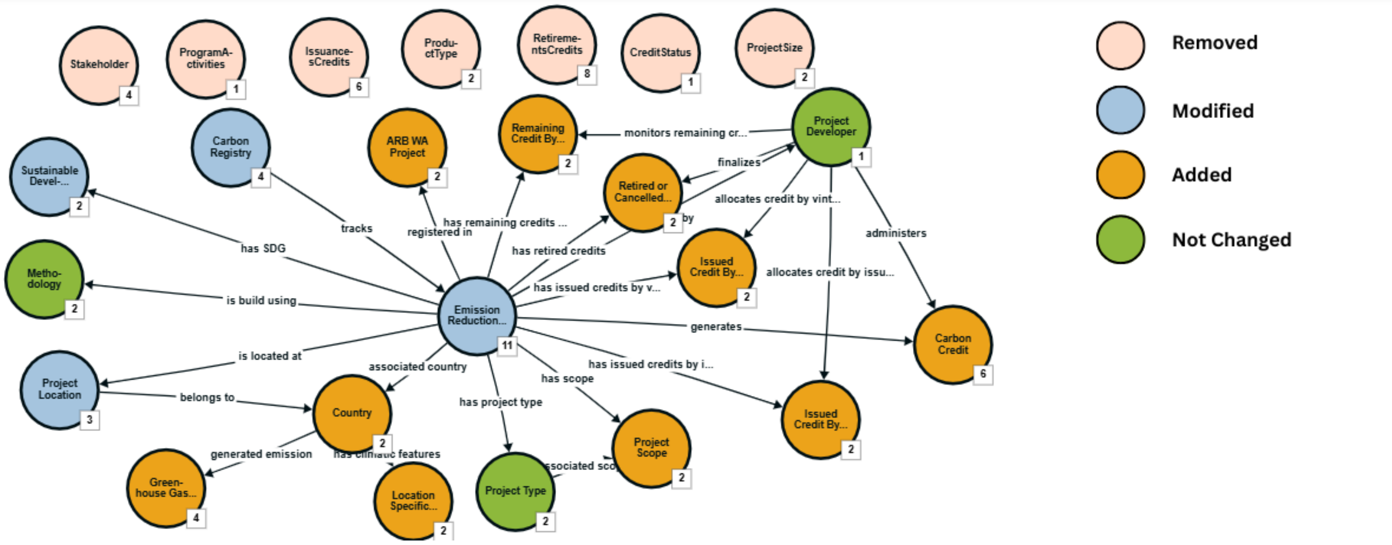

Figure 4.2 Visualization of the change in ontology

4.2 Knowledge Graph Construction

The first iteration of this research presented the CRA knowledge graph with a limited number of data points on emission reduction projects. It covered only 2951 emission reduction projects and one registry, which is the Gold Standard carbon registries.

The updated KG in this iteration now represents the emission reduction projects from the 4 top carbon registries: American Carbon Registries[4], Climate Action Reserve[5], Gold Standard[6], and Verra[7]. These registries cover 8777 different projects running in different parts of the world.

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[4] https://americancarbonregistry.org/
[5] https://www.climateactionreserve.org/
[6] https://www.goldstandard.org/
[7] https://verra.org/

Moreover, in the first iteration, we observed a navigational issue with the knowledge graph because the instances of the data used numerical values for representing the concepts and the relationships, which made it difficult for the user to interact with the system. For example, the knowledge graph had the information that the “1771” project is associated with the project developer “284”. These values represented a unique concept, but we are not sure about their meaning. So, we updated the design to showcase a label making it easier for the user to navigate the knowledge graph.

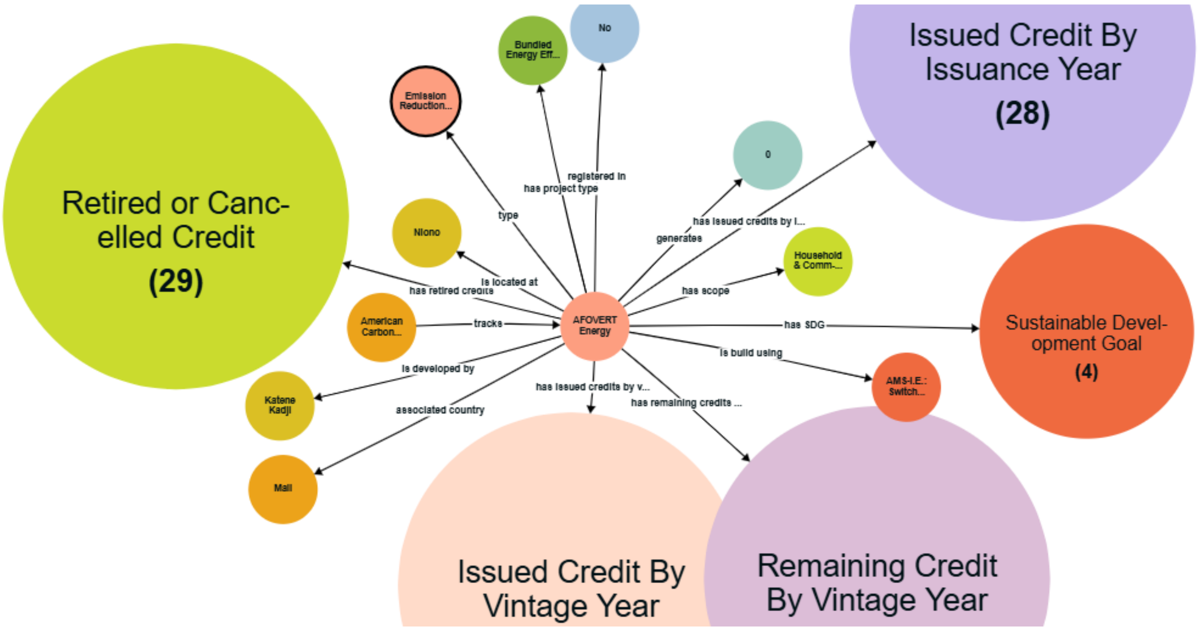

Figure 4.3 Knowledge Graph Visualization for "AFOVERT Energy"

The data, along with the CRA ontology, are implemented as a knowledge graph in the Stardog[8] platform, where stakeholders associated with the carbon credit ecosystem can interact with it and get insights. This helps them to make an informed decision about the ecosystem. Figure 4.3 shows an example of the Knowledge Graph, which demonstrates the relationship existing between an Emission Reduction Project “AFOVERT Energy” and other concepts.

5 Demonstration and Evaluation

The first iteration of CRA framework was evaluated based on its basic querying capabilities and the domain coverage of the initial ontology and knowledge graph using competency questions. This second iteration of the CRA framework development extends the previous evaluation process to support a more comprehensive and rigorous evaluation. In this iteration, the framework is evaluated and validated through the evaluation criteria (ease of use, stakeholder need fulfilment, coverage, consistency, accuracy and maintainability) at system level and user level. Evaluation results were collected and analysed to determine how efficient the CRA Framework in tackling the identified problems and challenges in iteration 1.

5.1 System Perspective

The comprehensiveness and completeness of the underlying knowledge graph are the focus of the system-level evaluation. This includes ontology coverage and data coverage. Ontology coverage helps to evaluate how much ontology is utilized by the knowledge graph, and data coverage helps to evaluate how well the knowledge graph represents the available data. Query coverage evaluates how well the system can answer the Competency Questions (CQs) representing real-world carbon credit management queries.

[8] https://www.stardog.com/

5.2 User Perspective

The framework's effectiveness in meeting user expectations (stakeholders need fulfillment (value) and ease of use) and whether the framework can help users with accurate output (query coverage and accuracy) is measured in user-level evaluation.

For the query coverage evaluation, we have taken the same six competency questions in natural language from iteration 1 <removed for refereeing> as listed in Appendix A, Table A3. The reason behind to take the same CQs as previous evaluate the artifacts against the same problem context. This helps us to determine the actual changes in the data added or removed through the system. These natural language queries are converted to SPARQL queries and executed on the framework and the results obtained were validated manually.

To evaluate stakeholders, need fulfillment (value) and ease of use, two use cases are developed: Environmental Impact Assessment and Ranking Project Developers. Environmental Impact Assessment involves optimizing carbon projects through environmentally similar projects (i.e., based on similar environment-related features of the project location). This use case leverages the knowledge graph to identify existing carbon projects with similar environmental characteristics to a proposed project. By comparing factors like average environmental temperature with successfully developed projects, project developers can select appropriate methodologies to develop new projects, enhance project efficiency, and gain insights into potential environmental challenges based on existing project data.

Ranking Project Developers focuses on identifying leading project developers with the help of a knowledge graph. Here project developers are ranked based on their track record within the carbon market by analyzing data like total carbon credits generated and total projects registered for the project developers. This analysis helps investors identify reliable and successful developers for potential investment and policymakers to evaluate the effectiveness of different project developers. It also helps project developers to benchmark their performance against competitors.

The summary of the evaluation processes is presented in Appendix A, Table A4. This evaluation's results provide insights into the framework's effectiveness, limitations, and areas for future improvement as discussed in following sections.

6 Results and Discussion

The results of the evaluation of our second iteration showed significant improvement from the previous iteration. Iteration 1 did not support the two use case scenarios, but we obtained valid outcomes executing them for the updated framework in iteration 2, revealing latest version has sufficient relationships and properties for industry applications. The evaluation of the ontology and data coverage reveals a significant improvement as well as the navigational issues present in the first iteration. The details of the result are presented below:

6.1 System Perspectives

Results obtained from the ontology coverage and the data coverage are presented in this section. There are 79 total concepts and properties modelled in the latest CRA ontology, and the knowledge graph uses 78 concepts and properties out of them, quantifying the ontology coverage as below.

ontology coverage = (78/79) * 100 % = 98.73 %

Similarly, in terms of data coverage, we compare the "project data" and "methodology data" import into the knowledge graph against data provided by the source. The desired data registries have a total of 8777 projects and 378 methodologies and CRA knowledge graph now contains all of them obtaining 100% data coverage.

Comparative visualisation of how ontology coverage and data coverage improved over two iterations are shown in Figure 6.1. This evaluation also shows that the ontology and the knowledge graph are maintained well. The newly updated version is consistent in covering more concepts and properties in terms of ontology coverage and is more consistent in covering available data from different registries in terms of data coverage. Moreover, we did not find any logical contradictions between the developed ontology and the real-world data while creating the knowledge graph using multiple registries. This suggests that the framework is consistent in representing the data across diverse sources.

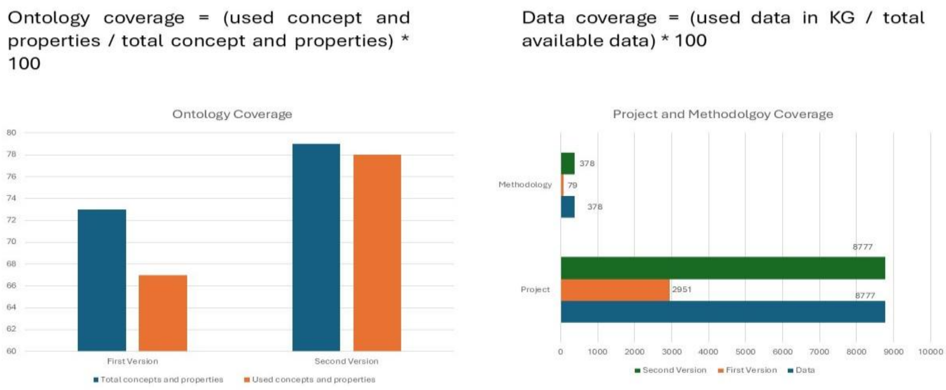

Figure 6.1 Ontology Coverage (left side) and Data Coverage (right side)

6.2 User Perspective

Results from implementing CQs and the Use Case scenarios are presented in this section.

For the evaluation through the competency questions, the natural language queries listed in Table 6.1 are converted into SPARQL queries as shown in Appendix A. For example, the competency question 5 from Appendix A, Table A5 is: *What are the methodologies used by the projects (e.g., "AFOVERT Energy" Project)?* The purpose of this query is to get the methodologies associated with the project "*AFOVERT Energy*" so that any project developer or investor investing in a similar project is aware of the possible methodology to be used and helps in their decision-making. Table A5. Appendix B, Figure B1, shows the SPARQL query execution of this question.

Table 6.1 below summarizes the SPARQL query output for all questions. This result was manually validated by authors to ensure accuracy, using source data.

	Competency Questions	Query Output
1	How many projects have been implemented in a specific geographic region (e.g. India)?	1586
2	What SDGs were met by the project that was successfully implemented (e.g. "Eritrea Community Boreholes" Project)?	Climate action; Good health and well-being; Gender equality; Clean water and sanitation
3	Who are the project developers involved in developing projects with project-type afforestation and reforestation?	New Zealand Forestry Removals Limited; Multiple Proponents; INOCAS; and so on.
4	What are the different carbon registries integrated in the Knowledge Graph?	Gold Standard; Verra; American Carbon Registry
5	What are the methodologies used by the projects (e.g. "AFOVERT Energy" Project)?	AMS-I.E.: Switch from non-renewable biomass for thermal applications by the user
6	How many credits have been issued/retired by a certain project (e.g. "AFOVERT Energy")?	541804

Table 6.1 Summary of query results obtained for all the CQs

These results showcase that the framework can accurately represent all the available real world data and eventually assists users in making decisions about the carbon credit ecosystem.

Similarly, SPARQL queries were designed and executed for the two use cases successfully as presented in Table 6.2.

Use Case	SPARQL Queries

1	Environmental Impact Assessment	PREFIX carbon: <http://surroundaustralia.com/carbon/model#>
		
		SELECT ?projectName ?countryName ?averageTemperature (GROUP_CONCAT(DISTINCT ?year; SEPARATOR=", ") AS ?years)
		(GROUP_CONCAT(DISTINCT ?annualEmissions; SEPARATOR=", ") AS ?annualEmissionsList)
		WHERE {
		GRAPH stardog:context:all{
		?project a carbon:Emission_Reduction_Project ;
		carbon:project_name ?projectName ;
		carbon:associated_country ?country.
		?country a carbon:Country;
		carbon:country_name ?countryName ;
		carbon:has_climatic_features ?climaticFeatures;
		carbon:generated_emission ?GhGEmission.
		?climaticFeatures a carbon:Location_Specific_Feature;
		carbon:average_yearly_temperature ?averageTemperature.
		?GhGEmission a carbon:Greenhouse_Gas_Emission;
		
		carbon:annual_greenhouse_gas_emissions_tonnes_of_CO2_equivalents ?annualEmissions;
		carbon:year ?year.
		
		}}
		GROUP BY ?projectName ?countryName ?averageTemperature
		Limit 20

2	Ranking Project Developer	PREFIX carbon: <http://surroundaustralia.com/carbon/model#>
		SELECT ?projectDeveloperName (COUNT(DISTINCT ?project) AS ?totalProjects) (SUM(DISTINCT ?totalCreditsIssued) as ?totalCreditsProduced)
		WHERE {
		
		?project a carbon:Emission_Reduction_Project ;
		carbon:project_name ?projectName ;
		carbon:is_developed_by ?projectDeveloper.
		?projectDeveloper a carbon:Project_Developer;
		carbon:project_developer_name ?projectDeveloperName ;
		carbon:administers ?carbonCredit.
		?carbonCredit a carbon:Carbon_Credit;
		carbon:total_credits_issued ?totalCreditsIssued.
		
		}
		GROUP BY ?projectDeveloperName
		ORDER BY DESC(?totalCreditsProduced) DESC(?totalProjects)
		LIMIT 5

Table 6.2 SPARQL Query representation of Use Case

This use case reveals framework capabilities for dealing with the complex tasks of users and fulfilling their needs. The query execution and the output for the ranking project developer is given in shown in Figure 6.1.

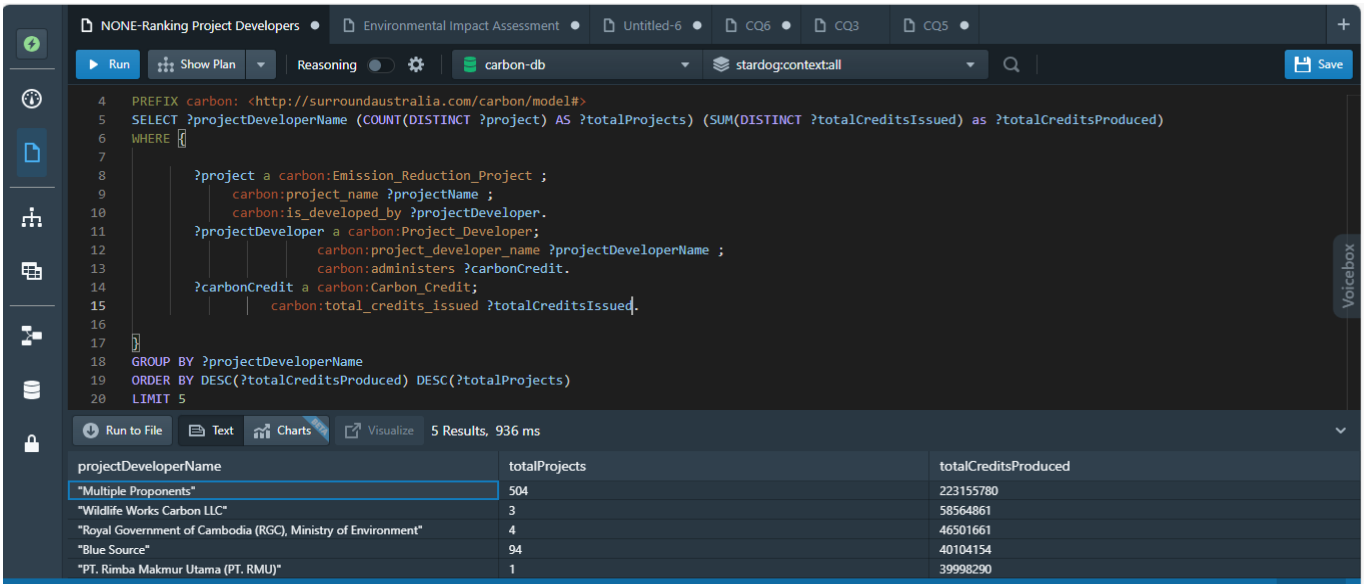

Figure 6.1 Ranking Project Developer

Regarding ease-of-use evaluation, if we compare the snapshot of a project, its properties, and its relationships through iteration 1 framework (Appendix B, Figure B2) vs Iteration 2 (Appendix B, Figure B3) we observe that visual navigation can be easily performed in 2nd version compared to the first.

7 Conclusion

This paper presents the second iteration of the Carbon Reduction Assessment (CRA) Framework. The new evolved version of the framework is more capable of handling the silos of data associated with the carbon credit ecosystems and the results obtained from the evaluation of the new updated framework showed the significant improvement from the previous one, as it is more capable in terms of supporting more comprehensive data integration, advanced reasoning, and improved the decision-making process.

Limitations of this study include limited evaluation with real-world end users. We also plan to explore how CRA framework can be integrated with other platforms and tools to be adopted by different stakeholders. In our future work we plan to publish this framework, including our ontology and knowledge graph as public resources for integration into systems catering for carbon credit assessment. We also plan to implement natural language-based query interface for this knowledge graph so non-technical users can easily interact with it.

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