Interoperability of Botswana's healthcare systems using semantic prescription ontologies

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ABSTRACT

The developing country of Botswana's health information system faces interoperability challenges mainly due to the lack of shared patient medical data and histories between private and public healthcare providers, which leads to increased medical errors, increased healthcare costs, and potentially fatal outcomes. This research proposes an intelligent electronic prescription ontology (IEPO) framework to share Botswana's patient electronic health records (EHRs) between private and public healthcare systems for a standardized and semantically rich data exchange. IEPO was evaluated for interoperability using the recall metric for completeness to capture the degree of all relevant information for exchange and the precision metric for accuracy performance to gauge the degree of error minimization during interoperability. The harmonic means of precision and recall called the F1-score, offered the overall interoperability performance. IEPO outperformed related works by 75% in recall, 54% in precision, and 76% in F1-score, demonstrating improved interoperability performance. Furthermore, IEPO was evaluated for correctness and expressiveness through competency questions via queries, results confirming correct and expressive responses.

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1. INTRODUCTION

Healthcare system interoperability refers to the ability of different healthcare systems, such as hospitals, clinics, laboratories, pharmacies, drug information sources, and electronic health records (EHRs), to seamlessly exchange and use healthcare information in a coordinated and meaningful manner [1], [2]. Botswana's healthcare system features a combination of isolated and non-interoperable public (government-owned) and private (non-government-owned) services like clinics and pharmacies, overseen by the ministry of health and wellness [3], [4]. The use of semantic electronic prescriptions has gained tremendous attention with the potential to bridge Botswana's healthcare system interoperability issues [5]. It involves the use of ontologies for the seamless exchange of information between distinct healthcare systems via electronic prescriptions [1], [6]. Ontologies in healthcare interoperability via electronic prescriptions provide a standardized and shared vocabulary for representing the domain-specific knowledge related to medications, prescriptions, and healthcare concepts that can be shared between isolated and non-interoperable systems [1], [6].

Botswana's healthcare system is non-interoperable and lacks access to patients' complete medical histories and medication records, leading to redundant tests, procedures, and prescriptions. This results in unnecessary costs and potential harm due to medical errors [7]. In Botswana, a patient can visit a private doctor who will prescribe a medication, and then visit another public doctor who will prescribe a different medication for the same health condition. Since the patient's medical history is not shared between the two doctors, this can lead to medical errors like drug-to-drug interactions where the two drugs prescribed by different doctors are incompatible, which may lead to adverse effects, hospitalization, or death [8]. Manual processes, such as printed prescriptions, faxing, and phone calls, also hinder data collection and analytics, limiting the ability to improve patient outcomes and contribute to evidence-based medicine [1].

It was observed from the literature that with the current frameworks, various healthcare stakeholders such as patients, pharmacists, and doctors encounter challenges in accessing patient prescription data and history electronically. The pharmacist faces limitations in recommending alternative drugs by requesting prescribers to modify prescriptions in situations of shortages or due to the cost of a particular prescription drug. In addition, none of the frameworks are open source; instead, they are all stand-alone and platform-dependent. Furthermore, the existing frameworks lack interoperability with vital signs healthcare monitoring, preventing the provision of alerts for abnormalities that fall outside standardized range values. Also, none of the present frameworks have undergone evaluation for interoperability, errors, correctness, and overall quality. This gap in assessment raises concerns about the reliability and effectiveness of these frameworks in facilitating seamless and error-free e-prescription processes within the healthcare system.

The literature reviw will focus on recent research published in peer-reviewed journals, conference proceedings, and other reputable sources. The time frame for selecting literature will be from 2013 to 2023. The review will follow a systematic approach to literature review, involving the following key steps: i) Literature searching using online academic databases including ScienceDirect, SpringerLink, IEEE Xplore, ACM Digital Library, Google Schoolar and Elsevier's Cloud Computing Journal to identify relevant articles using keywords such as "healthcare systems interoperability", "semantic prescription", "ontology interoperability". ii) Inclusion criteria of articles that specifically address healthacare interoperability using sematic prescriptions between 2013 and 2023. iii) Exclusion criteria of articles that are not focused on healthacare interoperability using sematic prescriptions. iv) Data extraction of key information from selected articles, including title, authors and years, healthcare interoperavbilit framewok gaps or features. v) Synthesis: organizing the extracted information into a summarized analysis table shown in Table 1 below which presents a comprehensive literature review that compares various healthcare electronic prescription interoperability frameworks based on ontologies, denoted as O1 [9], O2 [10], O3 [11], O4 [12], O5 [13], O6 [14], O7 [15], O8 [16], O9 [17], O10 [18], and O11 [19]. The evaluation encompasses key features and aspects of each framework to assess their effectiveness in addressing gaps and capabilities within the healthcare electronic prescription domain. An x denotes that the framework lacks a feature, which is also a gap.

Table 1 also shows the analysis of percentage gaps per framework and, on average 97% of gaps exist in literature and 91% of gaps exist per framework. Regarding portability aspects in Table 1, all frameworks (O1 to O11) exhibit a lack of open-source characteristics, requiring installation and being platform-dependent. The review indicates a uniform gap of 100% in this category across all frameworks. Addressing the semantic aspects, the majority of frameworks, such as O1 to O11, incorporate the use of ontologies, with an average score of 82%. However, none of the frameworks provide a SPARQL (an acronyme for SPARQL protocol and RDF query language) endpoint application programming interface (API), and free ontology downloads are not available across the board. Additionally, formal ontology development is lacking across all frameworks, contributing to a 100% gap in these areas. Moving on to ontology evaluation criteria, including domain knowledge ontology evaluation, interoperability evaluation, ontology pitfall evaluation, patient's history access, and prescription analysis, all frameworks (O1 to O11) exhibit significant gaps, reaching 100%. In summary, the analysis reveals that each framework, represented by O1 to O11, shares common challenges, resulting in a high percentage of identified gaps. The study underscores the necessity for improvements in open-source adoption, ontology development, and comprehensive evaluation criteria to enhance the effectiveness of e-prescription interoperability frameworks within healthcare systems.

Research contributions: i) Development of an interoperability electronic prescription ontology (IEPO) framework to seamlessly share e-prescription information between several healthcare entities like doctors, pharmacists, patients, medical aid, research, and machines. ii) The IEPO ontology significantly contributes to the research domain by being open source and freely accessible online for download encouraging widespread adoption and reuse, fostering further advancements in research. Download link: [shorturl.at/dqGY1]. iii) Evaluation of the IEPO framework for interoperability, errors, correctness, quality, using metrics like recall, precision, F1-score, and also via competency SPARQL queries.

Table 1. A comparison of ontology-based interoperability electronic prescription frameworks

Framework features		O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	Gap (%)
Portability Aspects	Open source	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Installation required	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Platform independent	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
Semantic Aspects	Uses ontologies	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	82%
	SPARQL endpoint API	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Free download	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Ontology development	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
Framework Evaluation	Domain knowledge	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Interoperability	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Ontology Pitfall	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
	Patient's history access	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	82%
	Prescription analysis	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	100%
Gaps % per framework		91%	91%	91%	91%	91%	83%	83%	100%	91%	100%	91%	

2. METHOD

This section will present the research method to build the IEPO framework to seamlessly exchange information between clinic and pharmacy systems in Botswana using semantic electronic prescriptions by leveraging ontologies. This research work presents a Botswana case study where there exist two stand-alone and non-interoperable healthcare systems; the public clinic and the private pharmacy. The clinic healthcare system comprises the following major concepts; doctor, clinic, patient, receptionist, patient's prescription, drugs within patient's prescription, patient's disease, patient's appointment, food taken by the patient, and patient allergies. The pharmacy healthcare system comprises the following major concepts; pharmacist, pharmacy, patient, patient's prescription, drugs within patient's prescription, patient's disease, food taken by the patient, and patient allergies. It is assumed that all pharmacies, clinics, doctors, and patients have all their details registered with the IEPO framework.

The IEPO framework is to achieve interoperability between the clinic and the pharmacy healthcare systems. The proposed framework evolves by developing clinic and pharmacy ontologies, merging them, and then evaluating them. The ontologies for the clinic and pharmacy systems will be developed to provide a common language that allows seamless communication and integration between these systems. The proposed ontologies offer a standardized approach to medication management, enhance patient safety, and enable efficient communication and collaboration between clinicians and pharmacists. By leveraging ontologies in the proposed framework, the clinic and pharmacy systems overcome the limitations of incompatible data models and ensure accurate and effective medication prescribing and dispensing. With the proposed framework, clinicians can access comprehensive and up-to-date information about medications, including their contraindications, side effects, and recommended dosages which helps clinicians make informed decisions and reduces the likelihood of errors or adverse drug events. The proposed IEPO framework is designed to seamlessly integrate with other healthcare systems, such as EHRs and clinical decision support systems (CDSS).

Figure 1 shows the adopted ontology development methodology called Methontology from [20], [21] to develop and evaluate the proposed IEPO framework. All the methontology steps will be followed to formally develop the IEPO ontology. The steps or activities include: i) acquisition, ii) specification, iii) conceptualization, iv) formalization, v) implementation, and vi) evaluation. The steps are described in the subsequent sub-sections.

2.1. Acquisition activity

Figure 1 shows the acquisition phase in green color which involves gathering information about the clinic and pharmacy systems concepts from the internet. Examples of concepts for several pharmaceutical clinics Botswana clinics, Botswana pharmacies, patients, online publications, related online ontologies, websites, sample image prescriptions from Google, e-prescription corpora, and general knowledge. This information gathering enables the extraction of common e-prescription concepts used within the clinic and pharmacy settings to develop the IEPO ontology.

2.2. Specification activity

Figure 1 also shows the ontology specification activity in orange colour which involves specifying the ontology domain and scope. The domain is healthcare and the scope is an ontology for healthcare interoperability using e-prescription. The ontology specification also captures the tools and technologies to be used which are not limited to Protégé for implementation, Jena Fuseki server for hosting IEPO as a triplestore database, SPARQL [22] which is a recursive acronym for SPARQL protocol and resource description framework (RDF) query language, representational state transfer (REST) protocol, and web ontology language (OWL).

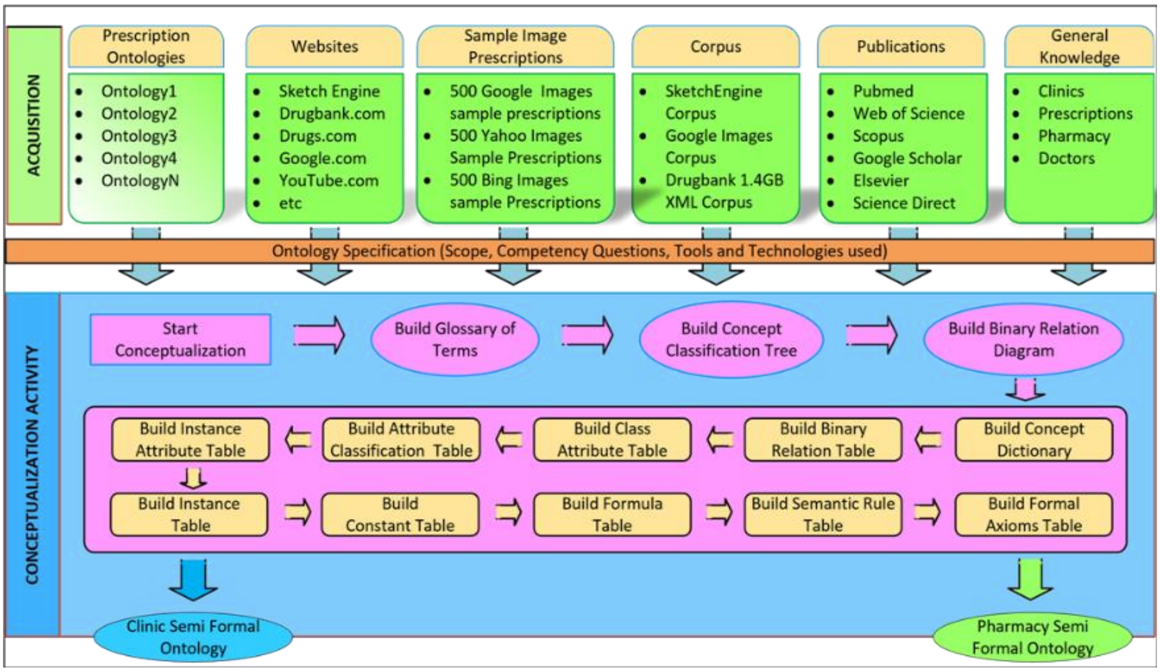
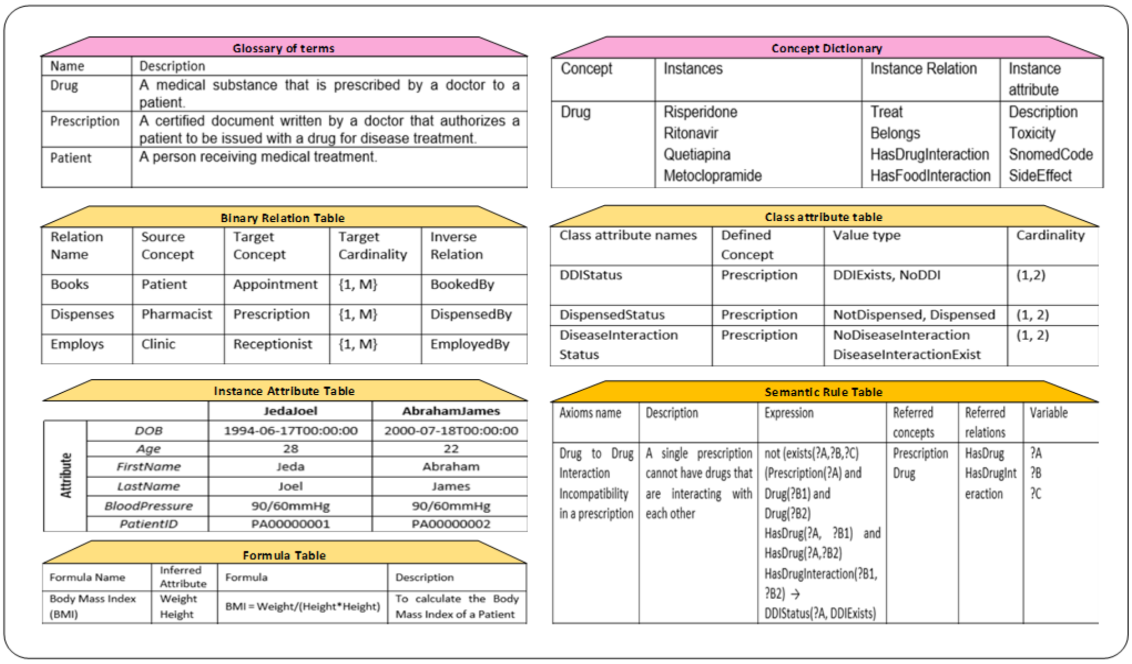


Figure 1. IEPO acquisition, specification, and conceptualization activities

2.3. Conceptualization

Figures 2-4 show the conceptualization of IEPO with the tables and diagrams showing part of the IEPO data. The high-level steps for methodology IEPO conceptualization are shown in Figure 1 in blue. The ontology conceptualization activities involves drafting tables and figures to document the information gathered from the acquisition phase and are shown in Figure 2 which include the following steps of building; i) a glossary of terms dictionary in Figure 2 that consists of the names of the concepts, objects, and data properties of the proposed IEPO ontology and their descriptions or definitions, ii) classification tree for both the clinic and pharmacy systems shown in Figures 3 and 4 respectfully showing a hierarchy of concepts covering the e-prescription, iii) binary relation diagram in Figure 5 which shows how the clinic and pharmacy concepts relate to each other in a diagram format in the form of object, predicate and subject, iv) concept dictionary in Figure 2 is a table containing all the domain concepts, instances of such concepts, class, and instance attributes of the concepts, and, optionally, concept synonyms for the clinic and pharmacy healthcare system, v) binary relation table in Figure 2 is a tabular representation that captures the binary relations between concepts in an ontology consisting of the relation name, source concept, target concept, target cardinality and inverse relation, vi) class attribute table shown in Figure 2 describes all the attributes in the class that is already included in the concept dictionary and consists of the class attribute name, value type and cardinality, vii) attribute classification table (not shown here) shows the classification of various attributes of the IEPO ontology, viii) instance attribute table shown in Figure 2 specify the following fields: its name; the concept it belongs to (attributes are local to concepts); its value type; and range of values (in the case of numerical values); minimum and maximum cardinality, ix) instance table shown in Figure 2 shows the class instances used in the IEPO ontology like, a specific drug name, a specific patient name, x) constant table (not shown here) contains the global constants values used in the ontology, xi) formula table shown in Figure 2 shows the mathematical formulars used in the IEPO ontology like calculating body mass index, xii) The semantic rule table defines the rules [23], [24] used in the ontology mainly to detect drug to drug interactions using semantic web rule language (SWRL) as shown in Figure 2 at the bottom such that a prescription cannot drugs that are interacting, xiii) Formal axioms are a table that includes logical expressions used in the ontology. Figures 2-4 defining and structuring the concepts, categories, relationships, and properties of the clinic and pharmacy ontologies. Conceptualization is a semi-formal way of representing an ontology before implementation.



Glossary of terms

Name	Description
Drug	A medical substance that is prescribed by a doctor to a patient.
Prescription	A certified document written by a doctor that authorizes a patient to be issued with a drug for disease treatment.
Patient	A person receiving medical treatment.

Concept Dictionary

Concept	Instances	Instance Relation	Instance attribute
Drug	Risperidone Ritonavir Quetiapina Metoclopramide	Treat Belongs HasDrugInteraction HasFoodInteraction	Description Toxicity SnomedCode SideEffect

Binary Relation Table

Relation Name	Source Concept	Target Concept	Target Cardinality	Inverse Relation
Books	Patient	Appointment	{1, M}	BookedBy
Dispenses	Pharmacist	Prescription	{1, M}	DispensedBy
Employs	Clinic	Receptionist	{1, M}	EmployedBy

Class attribute table

Class attribute names	Defined Concept	Value type	Cardinality
DDIStatus	Prescription	DDIExists, NoDDI	(1,2)
DispensedStatus	Prescription	NotDispensed, Dispensed	(1, 2)
DiseaseInteraction Status	Prescription	NoDiseaseInteraction DiseaseInteractionExist	(1, 2)

Instance Attribute Table

		JedaJoel	AbrahamJames
Attribute	*DOB*	1994-06-17T00:00:00	2000-07-18T00:00:00
	Age	28	22
	FirstName	Jeda	Abraham
	LastName	Joel	James
	BloodPressure	90/60mmHg	90/60mmHg
	PatientID	PA00000001	PA00000002

Formula Table

Formula Name	Inferred Attribute	Formula	Description
Body Mass Index (BMI)	Weight Height	BMI = Weight/(Height*Height)	To calculate the Body Mass Index of a Patient

Semantic Rule Table

Axioms name	Description	Expression	Referred concepts	Referred relations	Variable
Drug to Drug Interaction Incompatibility in a prescription	A single prescription cannot have drugs that are interacting with each other	not (exists(?A,?B,?C) (Prescription(?A) and Drug(?B1) and Drug(?B2) HasDrug(?A, ?B1) and HasDrug(?A,?B2) HasDrugInteraction(?B1, ?B2) → DDIStatus(?A, DDIExists)	Prescription Drug	HasDrug HasDrugInteraction	?A ?B ?C

Figure 2. IEPO conceptualization: glossary of terms, concept dictionary, binary relations table, class attribute table, instance attribute table, formula table, and formal axioms table

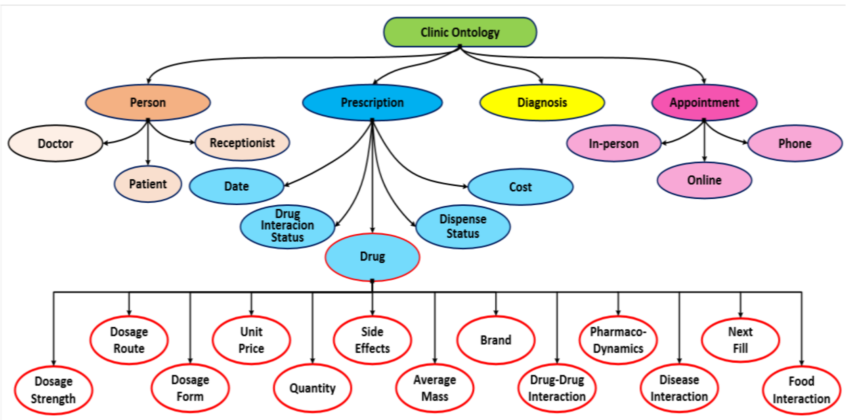


Figure 3. IEPO conceptualization: clinic concept classification tree

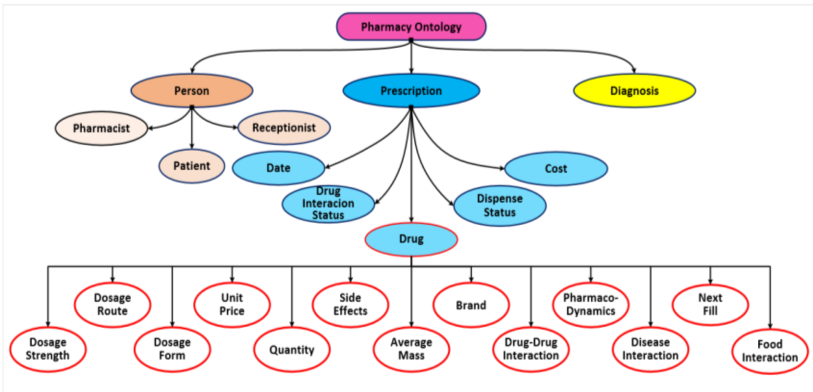


Figure 4. IEPO conceptualization: pharmacy concept classification tree

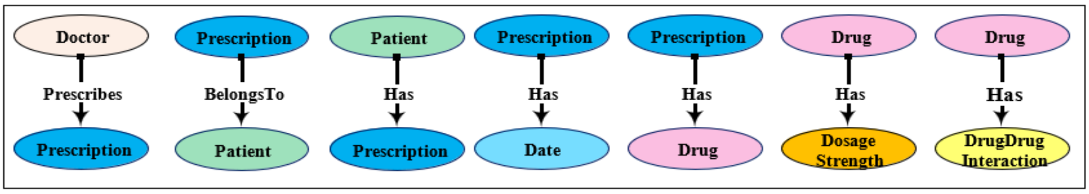


Figure 5. IEPO conceptualization: binary relation diagram

2.4. Formalization

Figure 6 shows the IEPO formalization. The formalization activity transforms the semi-formal conceptual model presented in the previous section into a formal model using the chosen ontology development tools and languages [20]. The output of formalization is an owl ontology file with an ".owl" file extension. The IEPO semi-formal ontology will be converted to a formal ontology called "IEPO.owl." The ontology development tool adopted is protégé [25], an open-source ontology editor and framework that can be used to create intelligent systems at no cost. The data from the conceptualization tables normally needs to be manually created in the protégé tool and this is a very tedious task that takes time due to massive conceptualization tables. Therefore, the conceptualization tables will be created in an excel spreadsheet and then batch imported into protégé using the cellfie plugin [26] as shown in Figure 7 using transformation rules to generate IEPO axioms in protégé and this has saved a tremendous amount of time. The output from protége formalization is an ontology file called "IEPO.owl" this file can be opened with any text editor, and it contains all the information about the ontology. It can be concluded that the "IEPO.owl" file is the ontology in text form and there is a need to host it for public consumption via online publishing.

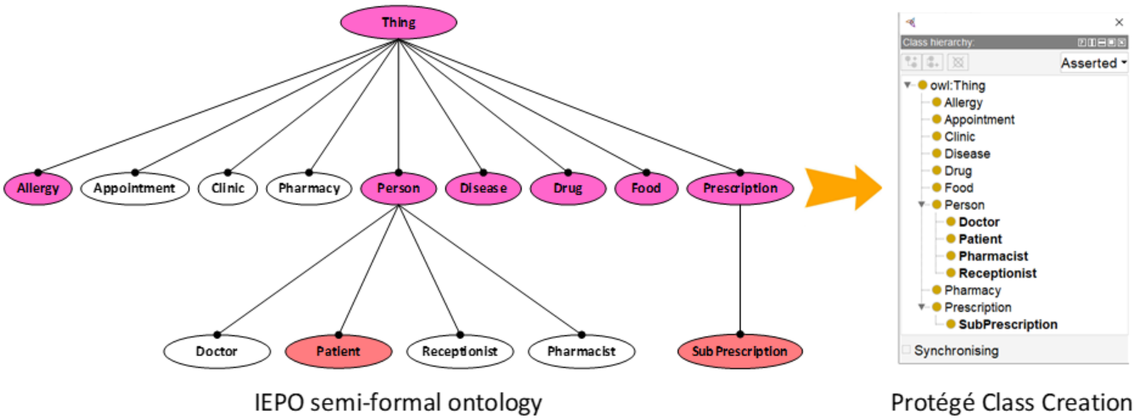


Figure 6. IEPO formalization: IEPO Class creation in protégé by converting the IEPO concept classification tree to protégé class hierarchy

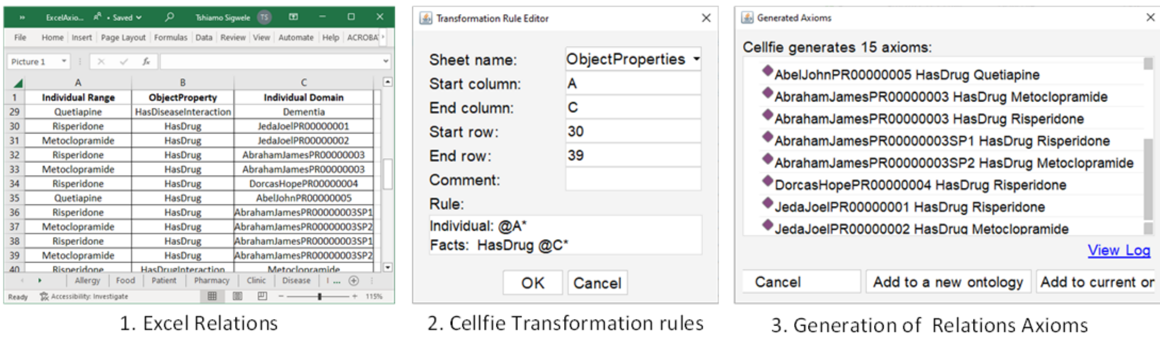


Figure 7. IEPO formalization: importing and linking IEPO individuals and relations into protégé using cellfie plugin

2.5. Implementation: IEPO hosting, publishing, and querying

Figure 8 shows the implementation phase of the methontology where the IEPO ontology is hosted on GitHub [27] as an open-source ontology available for free download (Download link: shorturl.at/dqGY1). The "IEPO.owl" file is also uploaded to a local triple store database called Jena Fuseki server [28], [29] which is used for locally hosting ontologies. Jena Fuseki then generates a web interface of an application programming interface called SPARQL endpoint in the form of an HTTP link at port 3030 to enable querying the IEPO ontology. The querying is done ontology SPARQL query language to retrieve and output the data from the IEPO ontology which is common for both the clinic and the pharmacy systems. The output of the query is in formats like the JASON, RDF, TRIPLE, using either the protege SPARQL tool or the Jena Fuseki SPARQL endpoint interface which can be accessed by any authorized entity (doctor, pharmacist, patients, and research) anywhere and any anytime showing that interoperability has been accomplished.

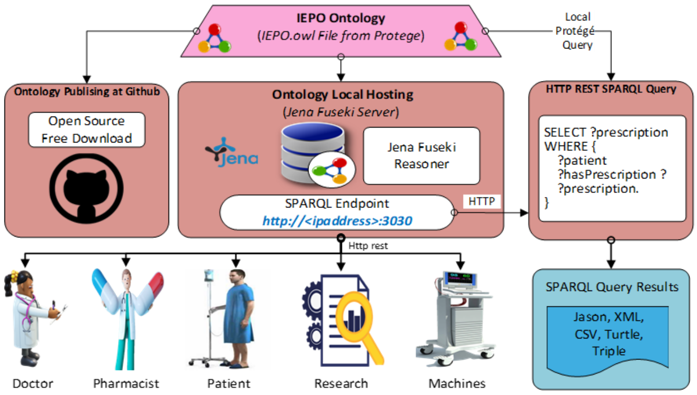


Figure 8. IEPO implementation phase: publishing, hosting, and SPARQL queries

3. RESULTS AND DISCUSSION

3.1. Evaluation for interoperability via corpus information retrieval approach

The proposed framework will be evaluated for interoperability between the clinic and the pharmacy by employing a corpus-based ontology evaluation methodology adopted from [30] and modified to fit our research as shown in Figure 9. Figure 9, in summary, shows that major prescription concepts are rated, sotted, and extracted from sketch engine corpus [31] of 1 million words and 500 Google sample prescriptions to be used to compare with the IEPO otology using information retrieval technology [32] using retrieval metrics for domain knowledge coverage. IEPO was evaluated for interoperability using recall metric for completeness to capture the degree of all relevant information for exchange or interoperability, and precision metric for accuracy performance to gauge the degree of error minimization during interoperability. The harmonic mean of precision and recall called the F1-score, offered the overall interoperability performance. Table 2 shows the results for comparing IEPO with related works for interoperability using precision, recall, and F1 metrics and the results show that IEPO outperformed related works by 75% in recall, 54% in precision, and 76% in F1-score indicating a high performance than current works in achieving interoperability.

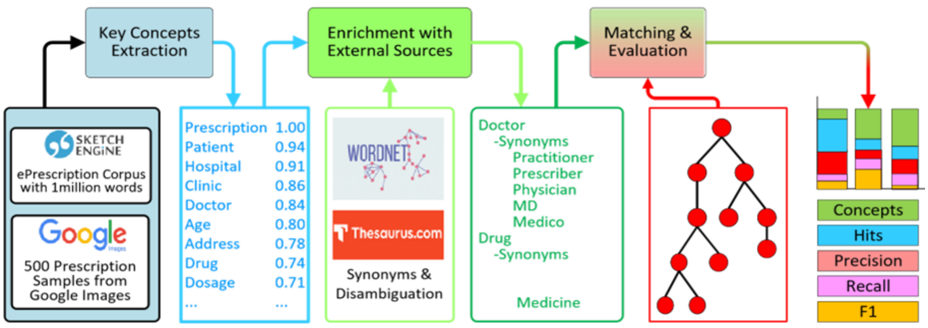


Figure 9. Corpus-based and information retrieval methodology for interoperability evaluation [30]

Table 2. Interoperability evaluation results: precision, recall, and F1-score

Concepts	IEPO	O1	02	O3	O4	O5	O6	O7
Concepts	31	14	13	13	14	18	25	15
Hits	24	3	3	11	5	5	8	4
Precision	0.77	0.21	0.23	0.84	0.35	0.27	0.32	0.27
Recall	0.08	0.01	0.01	0.04	0.02	0.02	0.03	0.01
F1	0.14	0.02	0.02	0.07	0.03	0.03	0.05	0.02

3.2. Evaluation for correctness via competency questions using SPARQL queries

Furthermore, IEPO was evaluated for correctness and expressiveness through competency questions via SPARQL queries [33], with results confirming correct and expressive responses to SPARQL queries. competency questions are the questions or queries the system should answer or return from the ontology server. The competency questions are used for testing the IEPO framework for interoperability:

- Competency question 1 (CQ1): List all prescriptions belonging to the patient named Jeda Joel. This is a prescription analysis query that is searched by either the doctor, the patient, or the pharmacist remotely. Competency question one is converted into a SPARQL query1 (Q1) as shown in Figure 10: the link prefix in the SPARQL is an international resource identifier (IRI) pointing to the IEPO ontology. The SPARQL query for the competency question reads, query the IEPO ontology and give me all prescriptions that belong to Jeda Joel. Table 3 shows the SPARQL query results of CQ1. The results show that the patient JedaJoel has two different prescriptions, which are Jeda-Joel-Jan-03-2022, a prescription issued on January 3rd, 2023, and Jeda-Joel-Jan-06-2022, a prescription issued on January 6th, 2022. The query can be viewed by the prescriber, patient, pharmacist, or other authorized entities remotely as it is now centralized and available to all. Security of the data will be the next development in the future. Figure 10 shows the SPARQL query for CQ1.

```
link: http://www.iepo.com/iepo SELECT ?patient
?prescription
WHERE {
            ?prescription? link:BelongsTo link:Jeda_Joel.
            }
```

Figure 10. A SPARQL query1 (Q1) for retrieving CQ1 information from IEPO

Table 3. Correct query results for CQ1

Patient	Prescription
Jeda Joel	Jeda-Joel-Jan-03-2022
Jeda Joel	Jeda-Joel-Jan-06-2022

- Competency question 2 (CQ2): What are the chances of the patient having COVID-19 (Vital signs temperature monitoring to detect COVID-19)? The SPARQL query2 (Q2) in Figure 11 is used to get the age and temperature of the patient and match with COVID-19 standard temperature ranges and age ranges and gives an alert if the patient has a high risk of having COVID-19.

```
SELECT ?Age ?Temperature  ?Age ?AgeStatus WHERE {

        o:AbrahamJames  o:Age ?Age.
        o:AbrahamJames  o:Temperature ?Temperature.
        BIND (
         COALESCE(
                IF((?Age > 1  && ?Age <=12)&& ?Temperature > 39, "Your  temperature is very high, there is a high probability
        you have COVID-19, contact GP", 1/0),
                IF((?Age > 12 && ?Age <=150)&& ?Temperature > 39.4, "Your temperature is very high, there is a high
        probability you have COVID-19, contact GP", 1/0),
                "You temperature is within the normal range."
                ) AS ?AgeStatus
            ).
}
```

Figure 11. A SPARQL query 2 (Q2) for retrieving CQ2 information from IEPO for COVID-19 risk alerts using temperature monitoring

In Figure 11, the bind and coalesce functions are used for manipulating age and temperature variables. Figure 12 shows the results for running the Q2 query where a patient called Abraham James with a body temperature of 37.7°C and age of 26 is checked via the IEPO system and the correct information was returned that the temperature is of normal range with fewer probabilities of COVID-19 infection as expected showing the that IEPO gives correct information when queried.

Figure 12. Correct SPARQL query results retrieved as expected for running Q2 on IEPO

4. CONCLUSION

This research focused on developing an IEPO framework to bridge the gap of healthcare interoperability in Botswana's non-interoperable public and private services like clinics and pharmacies. IEPO was evaluated for interoperability using the information retrieval-based recall metric for completeness to capture the degree of all relevant information for exchange, and precision metric for accuracy performance to gauge the degree of error minimization during interoperability. The F1-score was used as the harmonic mean of precision and recall to offer the overall interoperability performance. IEPO outperformed related works by 75% in recall, 54% in precision, and 76% in F1-score. In addition, IEPO was evaluated for correctness and expressiveness through competency questions via SPARQL queries, with results confirming correct and expressive responses to SPARQL queries. The proposed system can share, and exchange information remotely between various healthcare entities like doctors, pharmacists, and patients by querying a centralized ontology database hosted online. In the future, IEPO will be expanded to incorporate more ontology concepts and will also be evaluated with more evaluation metrics and other open-source tools.

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