Towards a Reference Architecture for Semantic Interoperability in Multi-Cloud Platforms

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***Abstract*—This paper focuses on semantic interoperability as one of the most significant issues in multi-cloud platforms. Organizations and individuals that adopt the multi-cloud strategy often use various cloud services and platforms. On top of that, cloud service providers may offer a range of services with unique data formats, structures, and semantics. Hence, semantic interoperability is required to enable applications and services to understand and use data consistently, regardless of the cloud service providers. The main goal of this study is to propose a reference architecture for semantic interoperability in multi-cloud platforms. Towards achieving the main goal, this paper presents two main contributions. First contribution is an extended cloud computing interoperability taxonomy, with semantic approach as one of the solutions for facilitating semantic cloud interoperability. Two fundamental semantic approaches have been identified, namely semantic technologies and frameworks which will be adopted as the main building blocks. Semantic technologies, such as ontologies, can be used to represent the semantics or meanings of data. Data may be reliably represented across multiple cloud platforms by employing a common ontology. This promotes semantic interoperability by ensuring that data is interpreted and processed uniformly within diverse cloud platforms. On the other hand, a framework offers a standardized and organized way for managing, exchanging, and representing data and services. For the second contribution of this paper, a review of recent (2018-2023) related works has been conducted by investigating the state-of-the-art of semantic interoperability in multi-cloud platforms. As a result, the proposed solution will be implemented in the context of a reference architecture. The reference architecture will act as a blueprint to systematically represent semantic interoperability in multi-cloud platforms using a hybrid approach of role-based and layer-based. Additionally, a semantic layer will be extended to the reference architecture to facilitate semantic interoperability.**

***Keywords*—Cloud computing; multi-cloud; reference architecture; semantic interoperability; semantic technologies**

I. Introduction

In the cloud computing landscape, cloud providers offer pay-as-you-go on-demand services to supply computing power, databases, storage, applications, and resources over the Internet [1]. Traditionally, cloud consumers adopted single-cloud strategy where all cloud-based services and applications are powered on one cloud provider. Each of these existing cloud providers use different interfaces, protocols, platforms, service description languages, architectures that often incompatible with competing cloud providers. Eventually, cloud consumers became dependent (lock-in) on a single cloud provider, making it almost impossible for them to switch services to different cloud providers.

In recent years, multi-cloud strategy has emerged due to the increasing demand from cloud consumers to uplevel the scalability, flexibility, security, and availability of cloud services and applications. The term “multi-cloud strategy” refers to the use of multiple independent cloud architectures that function as a single cloud architecture, where applications are distributed across these clouds in discrete pieces [2]. In other words, it offers support for different applications, services, and workloads on more than one cloud provider. Despite being a solution to avoid lock-in problems, it provides solutions in other business scenarios as well. For instance, when two or more organizations are collaborating and both mutually agreed for cloud resource sharing, then by adopting the multi-cloud strategy they can share resources from multiple cloud platforms. Hence, adopting the multi-cloud strategy can address challenges and capitalize on various benefits associated with cloud computing. In fact, IBM’s recent report revealed that 85% of companies are already adopting a multi-cloud strategy for their businesses [3].

It is crucial to guarantee cloud interoperability between multiple cloud platforms to achieve a harmonious and integrated cloud ecosystem. Interoperability, as described by the IEEE international standard language, is the ability of two or more systems, products, or components to exchange and use information [4]. In general, cloud interoperability is defined as the capacity of systems to effortlessly interoperate across different cloud platforms. Cloud interoperability ensures that the disparate cloud platforms can work together cohesively, enabling organizations to achieve specific goals and requirements. Due to most cloud providers having different services, technology, and interfaces, it can be difficult to achieve cloud interoperability across diverse cloud platforms [5]. Consequently, making the process of data exchange and communication between these diverse cloud platforms more difficult. Any solution to address multi-cloud interoperability must strike a balance between establishing the common cloud principles and supporting any form of cloud resources, regardless of its level of abstraction. In a nutshell, there are certain challenges to cloud computing interoperability, such as the difficulty of users and applications interacting with the cloud when providers do not employ common APIs [6, 7, 8, 9]. Furthermore, the diversity of network and storage architectures among different providers complicates infrastructure management [6].

As a result, it becomes the goal of this study to delve further into semantic approach to enable semantic interoperability in multi-cloud platforms. Along with this goal, this study aims at providing a solution that can offer flexibility, scalability, consistency, and standardization. Therefore, a strategic choice is to employ a reference architecture for enhancing semantic interoperability. A reference architecture offers a standardized framework that establishes consistency throughout various cloud platforms. It guarantees a common language and structure for data exchange between various cloud services by embracing industry-accepted standards and best practices. Thus, it promotes a more flexible and scalable multi-cloud solution that also reduces the risk of vendor lock-in. Essentially, in the complex landscape of multi-cloud environments, using a reference architecture becomes critical for organizations looking for a unified and interoperable foundation.

This study presents the background study of semantically interoperable cloud solutions using semantic approach. In addition to that, existing works that employed semantic approach for cloud interoperability are reviewed to gain insight about the requirements for semantically interoperable clouds. As a result, two contributions are presented in this study which are an extended cloud computing interoperability taxonomy based on the existing work by Ayachi et al. [10] and review of recent related works on reference architecture for semantic multi-cloud interoperability using semantic approach.

The remainder of this study is organized as follows. Section II describes the background study of cloud computing, multi-cloud computing, and cloud interoperability. Section III discusses the extended cloud computing interoperability taxonomy with two semantic approaches: semantic technologies and frameworks. Section IV presents a review of recent (2018-2023) related works on reference architecture for semantic interoperability in multi-cloud platforms, discussion of the review, identified research gaps, and future works. Finally, the conclusion is included in Section V.

II. Background Study

A. Cloud Computing

Ever since the field of cloud computing has gained its popularity, many authorities on the subject are trying to define the term "Cloud Computing". According to Mathew and Varia [1], cloud computing refers to the on-demand delivery of computing resources over an online cloud services platform via the Internet with pay-as-you-go pricing. Hurwitz and Kirsch [11] stated that cloud computing is the future evolution of the Internet where everything that individuals or organizations need can be offered as a service anytime and anywhere. Additionally, the National Institute of Standards and Technology (NIST) contributes to a more technical definition of the term, in which they identified cloud computing as a model that enables ubiquitous, practical, on-demand access to cloud resources that can be offered and released with minimal administration effort or engagement from cloud service providers [12].

According to NIST [12], a true cloud solution can be validated based on five basic characteristics of cloud computing, which are on-demand self-service, broad network access, resource pooling, rapid elasticity, and measure service. Currently, there are three service models that are prominent in the industry, namely Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). Each model is inextricably linked to one another, building a three-tier cloud service which ultimately forms cloud computing (see Fig. 1).

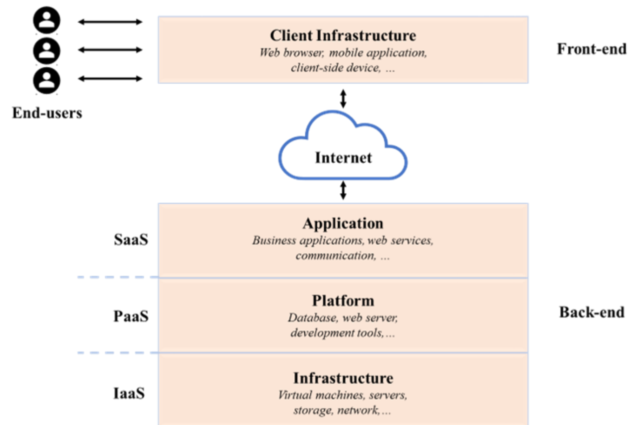

Fig. 1. Cloud computing architecture.

In the SaaS model, the applications are hosted by the cloud service providers and offered to the end users over the internet. It means that instead of installing the applications locally on the end user's computer, he/she may access the applications via the Internet [13]. The end users will only have control over the application settings, while the cloud infrastructure is fully managed by the cloud service providers. SaaS has multi-tenant architecture where it supports multiple tenants sharing a common infrastructure and the model offers services based on pay-per-use [14]. The PaaS model does not only provide a virtualized platform for the end users (i.e.: developers and deployers) to develop and deploy applications on the cloud, but it also offers database services [13]. The end users may use the tools, programming environments and configuration management tools that are provided by the cloud service providers based on a pay-per-use basis. This model can relieve developers of most of the system administration effort (e.g.: setting up and switching between development, test, and production environments), providing flexibility and scalability in PaaS [15]. The IaaS model consists of the hardware layer (e.g.: control processing unit (CPU), memory, disk, bandwidth) and the infrastructure layer (e.g.: virtual machine (VM)) that holds the servers, network and operating system provisioned by the cloud service providers [13]. The distinct feature of IaaS is scalability, also known as on-demand scalability, where the cloud infrastructure is rented as virtual machines based on a pay-per-use manner that dynamically scales in and out based on customers' demands [16].

In cloud computing environment, the cloud acts as a virtual computing environment with different options to deploy cloud services depending on the business needs. NIST listed four main deployment models which are public cloud, private cloud, community cloud, and hybrid cloud [12]. The public cloud offers general and public access to the cloud services and due to its open access, the security challenges for this model are critical because the resources are shared among multiple cloud consumers [17]. One simple example of a public cloud service is Google Drive that offers storage spaces located on the cloud for public users to access anytime and anywhere with internet access. The private cloud offers services to be deployed within an organization and is treated as an intranet functionality with the billing is subscription bases. Some examples include Amazon Web Services (AWS) Outposts, OpenStack, Microsoft Azure Stack, and others. The community cloud works in a similar way to the private cloud, but the model is exclusive to a group of organizations that share common interests, like compliance policies, security, and mission objectives. For instance, three companies shared the storage between them and therefore, reducing the installation costs if they shared a common infrastructure. Lastly, in the hybrid cloud model, the cloud infrastructure is set up of two or more types of cloud models (private, public, or community), each of which remains a separate legal entity, but are connected by standardized technology that enables the portability of data and applications [12].

In addition to the previous four deployment models, multi-cloud is a deployment model that deploys cloud services on multiple clouds and uses multiple cloud providers. One of the benefits of this deployment model is it allows redundancy, where resources are made available on different platforms to prevent data loss or a malware attack [18]. This study will be focusing on multi-cloud deployment model that will be explained further in the next section.

B. Multi-Cloud Computing

Multi-cloud computing refers to the adoption of multiple independent cloud architectures that act as a single cloud architecture, where applications are distributed across these clouds in discrete pieces [2]. As opposed to hybrid clouds, the components of a multi-cloud system are all distinct cloud systems rather than deployment models [19]. For example, a multi-cloud system is composed of two or more public clouds (see Fig. 2(a)), while a hybrid cloud system is a combination of a public cloud and a private cloud (see Fig. 2(b)).

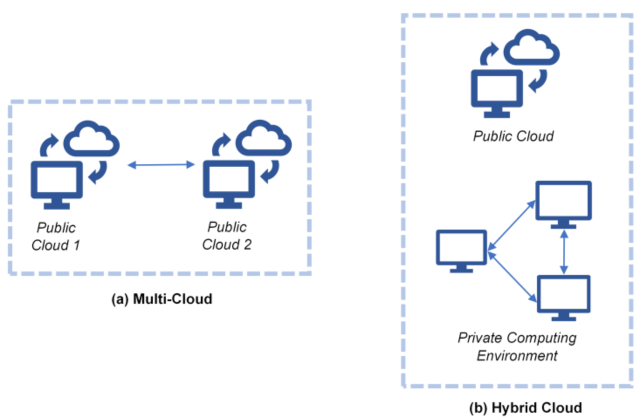

Fig. 2. Multi-cloud vs hybrid cloud deployment model.

Varghese and Buyya [6] emphasized that the changes in cloud computing environment are inevitable, and this leads to the changes of cloud infrastructure. Many existing cloud applications are hosted on data centers of a single provider, and thus creating several challenges like high energy consumption by a single large data center, centralized cloud data centers are susceptible to single point failures, and more. Therefore, they suggested by adopting the multi-cloud strategy these challenges can be overcome. However, due to the heterogeneous nature of multiple cloud providers, adopting the multi-cloud strategy can be challenging because of problems like different APIs, data formats, networks, and storage architectures across providers. It eventually prevents clouds from becoming interoperable, from exchanging data to migrating applications from one cloud to another. Hence, cloud interoperability in multi-cloud platforms is a critical issue to be handled.

C. Cloud Interoperability

According to IEEE international standard vocabulary, interoperability is referring to the ability of two or more systems, products, or components to communicate information and utilize that information [4]. Therefore, in general, cloud interoperability is the ability of the systems to interoperate across different cloud platforms. Nogueira et al. [20] suggested that the term “cloud interoperability” describes the capacity to create applications that integrate resources from different cloud providers to capitalize the unique features offered by each cloud provider.

Achieving cloud interoperability across multiple platforms is a challenge to overcome due to the distinct offerings, technologies, and interfaces by different cloud providers. Thus, complicates the process of merging or shifting resources and services between these different cloud platforms. The general issue with cloud interoperability is that different providers do not utilize common APIs, which makes it difficult for users and applications to interact with the cloud [6, 7, 8, 9]. Additionally, Varghese and Buyya [6] have listed other common issues like diverse network and storage architectures across different providers, significant programming effort is needed to develop a multi-cloud application due to the format differences of multiple providers, and manual management of tasks due to the lack of common interfaces. On top of that, Birje et al. [9] added that it is hard to detect the fault in data transmission across applications and clouds. As a result of these issues, consumer’s acceptance and adoption of multi-cloud strategy is hampered [8].

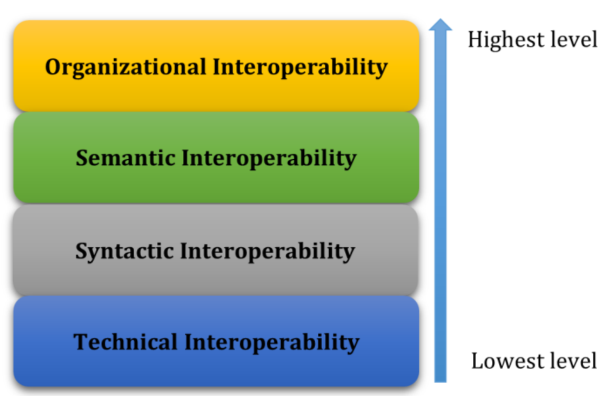

Fig. 3. Levels of interoperability and their correlations.

In general, most interoperability solutions are considered in four levels, with each level signifying a varying degree of compatibility and integration across cloud systems [10, 21, 22] (see Fig. 3). By having these interoperability levels, organizations can evaluate their ability to collaborate with various cloud providers and systems.

Based on Fig. 3, the interoperability levels and their correlations are described as the following:

1) Technical interoperability: This level is considered the lowest level of interoperability because it focuses on the technological facets of interoperability. For example, enabling the exchange of data and communication between multiple cloud systems across different platforms and infrastructures [10]. It covers technical aspects like interface specifications, data integration services, secure communication protocols, and data presentation [21].

2) Syntactic interoperability: In this interoperability level, it is often paired with the implementation of technical interoperability. This level is concerned with standardization of data formats to allow data to be exchanged among cloud systems [22]. It can be done by specifying the exact syntax and format of the data to be exchanged.

3) Semantic interoperability: This level is essential in interoperability between different systems as it tries to ensure that the meaning of the exchanged data can be understood and interpreted correctly [10]. In this level, users must share a common understanding of the data, metadata, and procedures used by various cloud platforms. To make data exchange and processing easier, standardized data models, ontologies, and metadata standards are frequently needed [22].

4) Organizational interoperability: This level addresses interoperability at a higher level of abstraction where it includes coordinating business processes, workflows, and automation across multiple cloud environments [21]. The interoperability at this level is dependent on the successful implementation of the previous interoperability levels: technical, syntactical, and semantic interoperability [22].

This study will be focusing on the semantic interoperability level in multi-cloud platforms. Multi-cloud strategy has developed as a strategic solution in the changing landscape of modern Information Technology (IT) infrastructure, enabling organizations to optimize performance, resilience, and cost-effectiveness by distributing their workloads over several cloud service providers. This paradigm shift reduces the risk of vendor lock-in and increases overall flexibility by allowing businesses to leverage the strengths of multiple cloud platforms. Thus, enabling semantic interoperability in a multi-cloud context is critical because semantic interoperability can improve application and data portability [23].

The term “semantic” is about understanding and making sense of words [24]. Semantic interoperability can be defined as the ability to exchange data in a meaningful way between two or more systems [25]. Semantic interoperability in multi-cloud platforms refers to the ability of disparate cloud systems and services to communicate seamlessly by having a mutual understanding of exchanged data and thus being able to use the data in a meaningful way. In a scenario where organizations opted for multiple cloud providers and services to meet their computing and storage needs, data exchange and processing can be a challenge due to unique data formats, structures, and policies offered by these providers and services. Semantic interoperability can address this challenge by guaranteeing that data and information can be exchanged effortlessly and understood across diverse cloud platforms without ambiguity and loss of meaning.

However, establishing semantic interoperability in the context of multi-cloud platforms has various challenges and limitations. At present, there are no industry-wide standards for semantic representation among various cloud providers [26]. But rather, most research activities and existing standard-setting entities produce various standardization efforts by resolving semantic interoperability problems from multiple perspectives. Another challenge of semantic interoperability is ensuring that performance, scalability, security, and other metrics are not compromised as these metrics are considered the quality attributes of any cloud systems [27]. For example, as the size and complexity of multi-cloud environments increase, ensuring semantic interoperability at scale becomes increasingly important because cloud computing services are scalable to meet the needs of the consumers. On top of that, implementing semantic interoperability is a complex task due to potential data model and ontology mismatches that can only be discovered during runtime [28]. It is due to the wide range of data models and ontologies utilized by various cloud services. Nonetheless, despite the challenges and limitations, research initiatives in semantic interoperability in multi-cloud platforms should continue for a variety of compelling reasons, including meeting evolving business needs, enhancing cross-cloud collaboration, mitigating vendor lock-in, optimizing resource utilization, and others.

III. EXTENDED CLOUD COMPUTING INTEROPERABILITY TAXONOMY

A well-defined taxonomy for semantic cloud interoperability is necessary to provide a better understanding of the topic and address the relationships between different elements of a multi-cloud ecosystem. The extended taxonomy is built upon an existing cloud computing interoperability (CCI) taxonomy by Ayachi et al. [10]. There are three main axes in Ayachi et al.’s taxonomy:

- CCI factors: It is comprised of five principal factors of CCI solutions, which are CCI deployment level, CCI interaction patterns, CCI consumer-centric, CCI approach, and CCI time-line perspective.
- CCI scenarios: It refers to the scenarios match with the use cases that have been studied previously, which includes provider-side scenarios and client-side scenarios.
- CCI solutions: It presents existing research efforts on proposed solutions to enable cloud interoperability.

To extend the existing CCI taxonomy, this study explores four types of approaches for semantic interoperability based on the work in [29, 30], and they are:

1) Semantic approach: The semantic approach primarily focuses on the semantic or meaning of data. In the cloud landscape, the implementation of semantic approach is through semantic web technologies, which includes defining shared ontologies, vocabularies, and semantic models to enable uniform data interpretation across cloud platforms [31]. One of the challenges of this approach is due to distinctive ontologies, it is difficult to align them and ensuring effective semantic mappings between them [32].

2) Standard-based approach: In order to facilitate semantic interoperability when exchanging data, the standard-based approach places a strong emphasis on the establishment of common standards, protocols, and data formats. Several standardization efforts have been made by standardization bodies and organizations that cover standards concerning development, security, management, deployment, and other matters related to the cloud platforms. In the work by Kaur et al. [29], the authors provided a complete list of organizations with their standardization projects. However, the main issue with this approach is no standard has been accepted universally to solve the semantic interoperability problems [26].

3) Model-based approach: The model-based approach centers around developing and deploying shared models that represent data structure and semantics. These models are developed using common modeling languages such as Unified Modeling Language (UML) or domain specific languages. This approach, however, is limited by the ability to transition between models and actual solution implementations [33]. Cloud Modelling Framework (CloudMF), which uses model-driven engineering to facilitate provisioning and deploying multi-cloud applications, is an example of a model-based approach [34].

4) Open libraries and open services: This approach relies on the use of abstraction layers and adapters, which support interoperability in the context of multi-cloud platforms. Some of the well-known open libraries are Apache jclouds and Apache Libcloud. For open services, some examples include RightScale, enStratius, and Kaavo [29].

This study will further investigate the semantic approach to fulfil the study's goal. Recent existing literature was studied with an aim to identify the best semantic approach for facilitating semantic interoperable clouds. In a survey by Adhoni [23], the author studies three popular approaches for building semantic interoperability solutions: semantics, frameworks, and standards. He claims that common APIs and data models are key solutions in semantic approach. DiMartino et al. [35] provide three categories of cloud portability and interoperability solutions: framework and model-based approaches, adapting methodologies, and standardization efforts. They stated that using semantic modeling can be beneficial in three aspects of cloud computing: to define the functionalities of applications and quality-of-service details regardless of the platforms, creating models for representing metadata, and enhancing service descriptions between different platforms. Additionally, semantic web technologies like Web Ontology Language (OWL), Web Ontology Language for Service (OWL-S), Resource Description Framework (RDF), SPARQL Protocol and RDF Query Language (SPARQL), and The Semantic Web Rule Language (SWRL) can be used to address these three aspects. According to Kaur et al. [29], the two approaches that are typically recommended for achieving semantic interoperability are standardized APIs and data models. In addition to the two approaches already stated, the authors noted from existing research that using a broker can help ease semantic interoperability by making it easier for users to match their needs with those of cloud vendors. In a systematic review by Tomarchio et al. [30], the authors have concluded their review with four interoperability approaches: open standards, semantics, model-driven engineering (MDE), and open libraries and services. Under the semantics approach, the authors claimed that employing semantic technologies (e.g.: OWL, SPARQL, and SWRL) for achieving semantic interoperability is a proven solution. Bouzerzour et al. [36] discovers that the most adopted approach for achieving cloud service interoperability is the use of semantic technologies, which is from the client's perspective. They have identified existing works that use APIs, ontology, semantic engine, inference rules, and semantic annotation to achieve semantic interoperability. As per Ramalingam and Mohan [26], the semantic level for portability and interoperability of cloud services can be addressed with semantic cloud ontology (e.g.: OWL and OWL-S) and frameworks. The authors have reviewed existing efforts on interoperable and portable frameworks based on three semantic technologies (i.e.: OWL, WSDL, and RDF) and discovered that the representation of semantic cloud services and resources lacks a common or uniform approach.

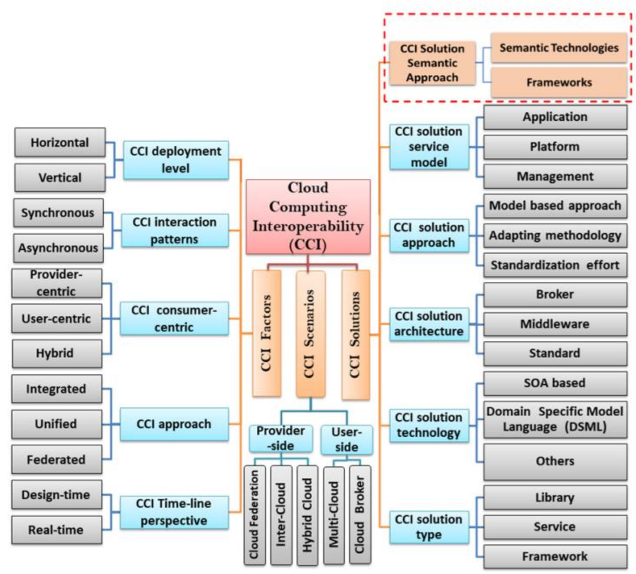

Fig. 4. Extended taxonomy for cloud computing interoperability.

As a result, considering the discussions in the preceding paragraph, this study suggests extending the existing cloud computing interoperability taxonomy by Ayachi et al. [10] by adding a sixth CCI Solution, namely CCI Solution Semantic Approach, with its two approaches which are Semantic Technologies and Frameworks. As shown in Fig. 4, they are depicted within a dashed rectangle. The details of CCI Solution Semantic Approach are discussed in the next subsections.

B. Semantic Technologies

In recent years, semantic technologies were frequently used to accomplish semantic cloud interoperability by providing a common platform for understanding and representing data and services in the cloud. Semantic technologies or sometimes called semantic web technologies comprised of a set of methods, tools, and standards that specifically deals with the meaning and interpretation of data to be understood by machines and applications [36]. Once data is interpreted correctly, these machines and applications can process the data more intelligently.

Current literature agrees that ontologies are the core element of semantic solutions [36, 26, 37, 38]. An ontology reflects domain knowledge, where the ontology classes are typically depicted using graphical models, as models are considered to have explicit semantics [39]. Ontologies are often expressed in a formal language that can be interpreted by both humans and machines, like RDF and OWL. Applications such as information retrieval, semantic web, natural language processing, data integration, and knowledge management all heavily rely on ontologies. They provide a shared understanding among various systems and users by offering an organized and standardized means of representing and exchanging knowledge. Al-Sayed et al. [40] stated that three fundamental components build up an ontology: classes (or concepts), objects (or instances), and properties (or relations). The class is used to describe a collection of instances with comparable characteristics. Properties are used to indicate relationships between instances (i.e.: object property) or between instances and data (i.e.: data-type property). Besides ontologies, other semantic technologies that have been employed for semantic cloud interoperability are semantic APIs, semantic engine, inference rules, and semantic annotations [36].

One of the recent works on ontologies for semantic interoperability is MIDAS-OWL, which is an ontology built on OWL to formally represent the interactions between SaaS and Data as a Service (DaaS) [41]. The proposed ontology connects data among DaaS by rewriting queries with semantically identical properties. PaaSport semantic model is another OWL-based ontology to best support an algorithm for semantic matchmaking and ranking, which suggests the most appropriate PaaS offerings to the application developer [42].

C. Frameworks

According to Partelow [43], the term "framework" has multiple definitions and purposes depending on the field in which it is used. Hence, the author provides several notable definitions of the term “framework” in different contexts and fields of study. It can be concluded that a framework is a methodical and well-structured collection of ideas, procedures, and tools that serves as a basis for creating and addressing complex problems. In software development, for example, a framework provides scaffolding for guiding the overall design and implementation of a system or a project. In addition to providing a pre-established structure and design patterns, frameworks frequently come with tools and libraries that facilitate the development process. Therefore, it offers several benefits to software development by helping to speed up the development process, ensure consistency across projects, promotes flexibility and easy to reuse the components.

Due to businesses’ growing interest in multi-cloud strategy and the need to ensure that the clouds are semantically interoperable, the solutions for semantically interoperable clouds demand an efficient framework. Frameworks that support semantic cloud interoperability, either through standardized interfaces or protocols, can be useful when implementing solutions within the context of a reference architecture. This is because reference architecture acts as a blueprint or template for the design and development of concrete architectures in IT domains. It is considered as a one-to-many relationship between a particular implementation and concrete architectures, and thus, it is an abstract representation of that architecture [44]. It outlines the recommended components, interfaces, and protocols to enable seamless interaction and integration between cloud platforms. It also includes guidelines and best practices for security, scalability, performance, portability, interoperability, and management [45]. Furthermore, Valle et al. [46] revealed that existing works did not explicitly propose techniques (e.g.: models, procedures, or other terminology) to characterize interoperability in reference architectures. As such, the authors emphasized the need to suggest novel approaches for modelling interoperability in reference architecture and for addressing interoperability during architecture instantiation. Therefore, this study suggests that building a cloud solution using a reference architecture is seen as a fitting approach that can contribute to a uniform representation of semantic-based solutions.

Existing prominent organizations and interest groups have produced their own reference architectures or open frameworks and made them freely available for generating further innovative solutions. These architectures or frameworks are offered as open standards that acknowledge the various needs for heterogeneous ecosystems and have been set as a rule for cloud interoperability. Bakshi and Beser [47] review eleven existing reference architectures from standards bodies, consortiums, and forums. In their review, they emphasized that the NIST Cloud Computing Reference Architecture (CCRA) has generic cloud computing architectural building blocks with five major actors (i.e.: Cloud Consumer, Cloud Provider, Cloud Carrier, Cloud Auditor, and Cloud Broker). Each actor has its own roles that are important for managing and providing cloud services in the cloud [45]. Other reference architectures are concerned more on the compliance towards standards, networking and communication services, security, cloud infrastructure, cloud management systems, and cloud interoperability.

Sana et al. [48] review nine existing reference architectures by NIST, Oracle, Distributed Management Task Force

(DMTF), International Business Machines Corporation (IBM), Hewlett-Packard (HP), Cisco, Cloud Security Alliance (CSA), Storage Networking Industry Association (SNIA), and Elastra. The authors concluded with three categories of reference architectures in cloud computing, and they are:

1) Role-based: In this form of reference architecture, the services and activities are matched to roles like cloud service providers and cloud consumers. The architectures of this kind of categories are NIST, Oracle, and DMTF.

2) Layer-based: This form of reference architecture maps services and activities to various architectural layers, including resource layers, application layers, service management layers, and security layers. The architectures of this kind of categories are IBM, HP, and Cisco.

3) Context-based: Reference architectures of this kind offer specific configurations to suit customer needs and make their adoption easier. The architectures of this kind of categories are CSA, SNIA, and Elastra.

Therefore, based on the review by Bakshi & Beser [47] and Sana et al. [48], out of all the reference architectures, the NIST CCRA and IBM CCRA can easily be adapted to this study. These two CCRAs can be a good reference and guideline as they systematically represent the reference architecture using role-based and layer-based architectures. Hence, a semantic interoperability layer can be added as part of the proposed reference architecture for semantic multi-cloud interoperability.

IV. Related Works and Discussion

Even though several cloud computing reference architectures have been produced by notable organizations and interest groups (e.g.: NIST, IBM, AWS, and Google Cloud), the main purpose of these reference architectures is to establish common frameworks and guidelines for industry-wide adoption. Typically, standard-based architectures are more stringent and directive to guarantee uniformity and compliance amongst implementations [49]. As a result, reference architectures have been produced by research initiatives to broaden the possibilities available to other researchers and industries. Research-driven reference architectures are often developed to explore new and test ideas, concepts, or technologies. They may not necessarily aim for immediate standardization.

Therefore, this study aims at reviewing recent (2018-2023) research-driven reference architectures for achieving semantic multi-cloud interoperability. Thirteen recent related works on semantic interoperability in multi-cloud platforms are selected, while the works in other domains such as the Internet-of-Things (IoT), Artificial Intelligence (AI), Blockchain, and big data are excluded. The review focuses on the authors' contributions and summarizes the findings based on the six CCI Solutions (as depicted in the extended cloud computing interoperability taxonomy in Fig. 4). The findings are reported in Table I.

As shown in Table I, it is found that most of the semantic approaches are using ontologies, like OWL, OWL-S, and RDF. This indicates that ontologies are proven solutions for semantic interoperability. Other than ontologies, APIs are among the popular solutions as they can serve as common interfaces between different platforms. The solutions are implemented as models, common architectures, and even toolkits. For the models, most works proposed semantic models that can be employed as part of a framework, stored as libraries, and adopted in semantic engine or semantic layer. For the common architectures, they are represented using layer-based, role-based, and hybrid of both. Apart from that, not every proposed solution aims to address interoperability across the three cloud service models (i.e.: IaaS, PaaS, and SaaS). Most solutions address interoperability independently for each of the three cloud service models. Existing works also prefer providing solutions based on broker and middleware architecture. Standards are the least preferred in developing research-driven architectures. SOA based are seen as the most favorable implementation of the solutions. It might be because broker and middleware architectures can effectively complement the SOA based implementation. The type of solutions produced is mostly frameworks and libraries. Finally, the limitations of each reviewed work are presented in the last column of Table I.

TABLE I. Review of Recent Related Works

Related Works (2018-2023)	**CCI Solutions**						**Limitations**
	CCI Solution Semantic Approach	***CCI Solution Service Model***	***CCI Solution Approach***	***CCI Solution Architecture***	***CCI Solution Technology***	***CCI Solution Type***	
FCLOUDS framework to achieve semantic interoperability in multi-clouds [50]	API, Open Cloud Computing Interface (OCCI)	Application	Model based approach	Middleware	DSML	Framework	Limited to the OCCI standard.
A common interoperable model for cloud computing [48]	API, Architecture is a hybrid of role-based & layer-based	Application, Platform, Management	Adapting methodology	Standard	SOA based	Framework	API is insufficient for semantic understanding.
PaaSport semantic model: An ontology for a platform-as-a-service semantically interoperable marketplace [42]	OWL, RDF, API, Service Level Agreement (SLA), Semantic model (layer-based)	Platform	Model based approach	Broker	SOA based	Service	The solution is specific to PaaS offerings.
CloudLightning Ontology (CL-	OWL, Semantic engine	Platform, Management	Model based approach	Middleware	SOA based	Library	Currently, the system cannot evaluate

Related Works (2018-2023)	CCI Solutions						Limitations
	CCI Solution Semantic Approach	*CCI Solution Service Model*	*CCI Solution Approach*	*CCI Solution Architecture*	*CCI Solution Technology*	*CCI Solution Type*	
Ontology): An ontology for heterogeneous resources management interoperability and HPC in the cloud [51]							performance, resource utilization, and energy consumption.
PacificClouds: A flexible microservices based architecture for interoperability in multi-cloud environments [52]	API, SLA, Microservice	Management	Adapting methodology	Broker	SOA based	Service	API is insufficient for semantic understanding. The implementation of semantic SLA is not clearly stated.
EasyCloud: A rule-based toolkit for multi-platform Cloud/Edge service management [53]	API, toolkit	Application	Adapting methodology	Broker	SOA based	Library	API is insufficient for semantic understanding. The solution is specific to SaaS offerings.
Cloud interoperability based on a generic cloud service description: Mapping OWL-S to GCSD [54]	Mapping rules (OWL-S), Pivot model (mediator for transforming different cloud service description languages to the GCSD).	Application.	Model-based approach.	Middleware.	DSML	Library	The solution is specific to SaaS offerings.
EasyCloud toolkit to effectively support the creation and usage of Multi-cloud Systems (MSs) [55]	API, toolkit	Application	Adapting methodology	Broke	SOA based	Library	API is insufficient for semantic understanding. The solution is specific to SaaS offerings.
Semantic Interoperability Framework for IAAS Resources in Multi-Cloud Environment [56]	RDF, OWL, SPARQL, Ontology mapping	Management	Model-based approach	Broker	SOA based	Framework	The solution is specific to IaaS resource management.
MIDAS: A domain specific language to provide middleware for interoperability among SaaS and DaaS/ DBaaS through a metamodel approach [57]	API, Semantic mapping, Structured Query Language (SQL) or Not Only SQL (NoSQL), Metamodel (Eclipse Modeling Framework (EMF)	Application	Model-based approach	Middleware	DSML	Framework	Limited to Middleware for DaaS/DBaaS and SaaS (MIDAS) architecture.
Cloud Enterprise Resource Planning (ERP) API Ontology [58]	OWL	Application, Platform, Management	Model-based approach	Middleware, Broker	SOA based	Framework	No ontology evaluation in a practical application for business data migration between cloud ERP providers.
PaaS and IaaS Resource Semantic Interoperability Framework (extended from their previous work) [59]	RDF, OWL, SPARQL, Ontology mapping	Platform, Management	Model-based approach	Broker	SOA based	Framework	The solution is specific to PaaS and IaaS resource management.
Cloud Interoperability Pivot Model (CIPiMo) for cloud service interoperability [60]	Mapping rules (WSDL and OWL-S), Pivot model (mediator for transforming different cloud service description languages to the GCSD)	Application	Model-based approach	Middleware	DSML	Library	The solution is specific to SaaS offerings.

Even though several research efforts have been done related to the topic of this study, it is found that existing works on reference architectures for semantic multi-cloud interoperability are still not in a mature stage and prompting for future works. Some research gaps that can be identified from the review are as the following:

- The integration of semantic-based solutions (e.g.: semantic model) within a framework (e.g.: reference architectures) is not explicitly and uniformly represented. This is an essential consideration in current research given the growing interest in multi-cloud strategy and the fact that multi-cloud platforms are inherently diverse.
- Cloud interoperability solutions are not inclusive of three cloud service models (i.e.: IaaS, PaaS, and SaaS). Most of the works address interoperability independently across the three cloud service models. It is important to consider cloud interoperability vertically and horizontally across the three cloud service models.

By identifying the research gaps in recent related works, this study aims to propose future works that attempts to solve these problems. Therefore, the following are suggested for future works of this study:

- To identify necessary requirements for developing ontologies and reference architectures.
- To develop a semantic model utilizing ontologies and other semantic technologies in order to facilitate semantic interoperability in data exchange across various cloud platforms.
- To develop a reference architecture for semantic multi-cloud interoperability by adapting a hybrid of role-based and layer-based architectures with an extended semantic interoperability layer. In addition to that, there is a need to identify the required roles (actors) and layers for the proposed reference architecture.
- To implement the proposed semantic model and reference architecture against use cases in multi-cloud platforms.

V. CONCLUSION

Semantic interoperability in multi-cloud platforms enables uniform interaction and interpretation of data and applications across diverse platforms. However, achieving semantic interoperability remains a challenge, and research efforts in this area are ongoing. Although professional groups or organizations have developed standard solutions for semantically interoperable clouds, research-driven initiatives are still required to enhance semantic interoperability by delivering uniform blueprints.

This study explores the significance of multi-cloud computing in today’s dynamic and complex IT landscape. As organizations increasingly rely on cloud services for their diverse computing needs, understanding the implications and benefits of adopting a multi-cloud strategy becomes paramount. The study investigates how multi-cloud environments can address the evolving requirements of scalability, flexibility, and other requirements while navigating interoperability concerns. By examining the recent related works on two main areas, which are semantic interoperability and reference architecture, this study aims to provide a strategic solution in the form of a reference architecture for semantic interoperability in multi-cloud platforms. Furthermore, the review on recent related works reveals that the lack of widely accepted semantic models and frameworks indicates that the field of study is still in its infancy and needs further development.

Therefore, two contributions have been proposed in this study, and they are:

- An extended CCI taxonomy by adding the semantic approach which consists of semantic technologies and frameworks that are considered crucial approach to enable an effective semantic interoperability in multi-cloud platforms. This taxonomy can serve as a knowledge base for future researchers and promote consistency across different research studies.
- A review of recent related works on semantic interoperability in multi-cloud platforms, highlighting the current CCI solutions employed by the authors in their proposed work. The review includes the limitations of each work, and thus prompting for future work. The result of this review is not only important for studying the current technologies used for semantic interoperability, but also for identifying the research gaps that may present in current research.

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