

Inter-Cloud Architectures and Application Brokering: Taxonomy and Survey

Nikolay Grozev^{1*†} and Rajkumar Buyya¹

¹Cloud Computing and Distributed Systems (CLOUDS) Laboratory, Department of Computing and Information Systems, The University of Melbourne, VIC 3010, Australia

SUMMARY

Though Cloud computing itself has many open problems, researchers in the field have already made the leap to envision Inter-Cloud computing. Their goal is to achieve better overall Quality of Service (QoS), reliability and cost efficiency by utilizing multiple clouds. Inter-Cloud research is still in its infancy and the body of knowledge in the area has not been well defined yet. In this work, we propose and motivate taxonomies for Inter-Cloud architectures and application brokering mechanisms. We present a detailed survey of the state of the art in terms of both academic and industry developments (20 projects) and we fit each project onto the discussed taxonomies. We discuss how the current Inter-Cloud environments facilitate brokering of distributed applications across clouds considering their non-functional requirements. Finally, we analyse the existing works and identify open challenges and trends in the area of Inter-Cloud application brokering. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Cloud computing has been attracting the interest of the Information and Communications Technology (ICT) community since 2007 resulting in a massive amount of industry developments. It has been seen as the next logical step after Grid computing on the way to utility computing, where computing resources are available as subscription utility service just like water and electricity. Cloud computing has been defined as a type of parallel and distributed system providing virtualized resources in a pay-as-you-go fashion over the Internet [1, 2, 3]. From business perspective it is widely viewed as an economical model for renting technical resources [4]. Being able to rent resources on demand and to avoid upfront investments in hardware and licenses proves to be very enticing for enterprises in a dynamic and unstable business environment.

However, the standard Cloud computing model, where a client utilizes a single cloud data centre introduces several challenges. A cloud service unavailability can leave thousands of customers relying solely on it without access to essential and paid for resources. Also relying on a single cloud data centre makes it hard to implement adequate responsiveness and usability to clients distributed worldwide. These factors preclude the usage of multiple clouds (i.e. an Inter-Cloud) in order to achieve better QoS, reliability and flexibility.

*Correspondence to: Nikolay Grozev, Cloud Computing and Distributed Systems (CLOUDS) Laboratory, Department of Computing and Information Systems, The University of Melbourne, VIC 3010, Australia

†E-mail: ngrozev@student.unimelb.edu.au

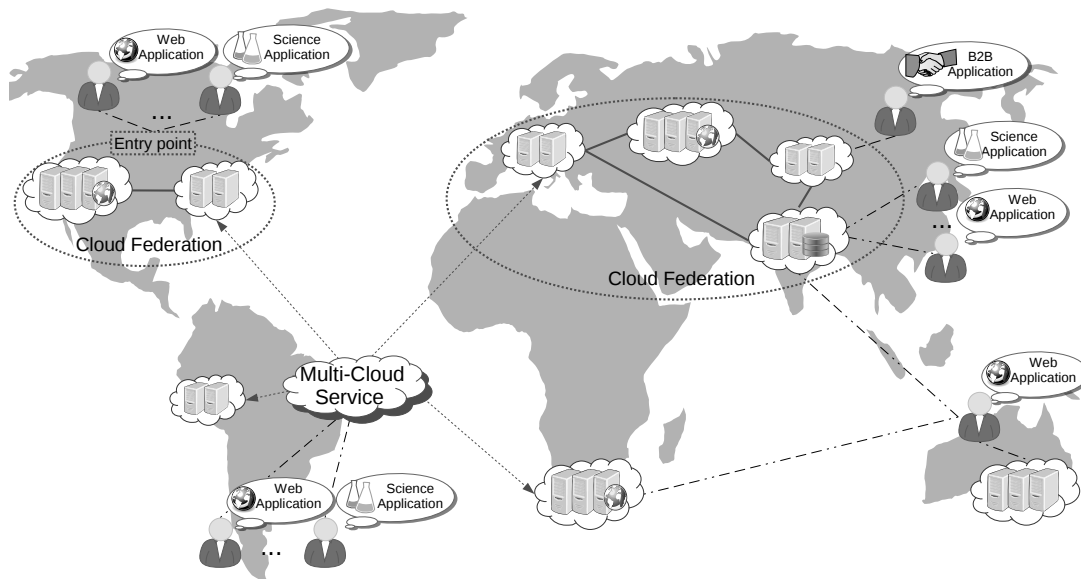


Figure 1. An overview of Inter-Cloud approaches and use cases.

The first academic publications about Inter-Clouds appeared a couple of years after the advent of Cloud computing and include the following seminal works - [5, 6, 7, 8, 9]. The term Inter-Cloud has been described as a cloud of clouds [10] and a formal definition is provided in Section 2. Essentially an Inter-Cloud allows for the dynamic coordination and distribution of load among a set of cloud data centres - see Figure 1.

The benefits of an Inter-Cloud environment for cloud clients are numerous and can be broadly summarized as:

- **Diverse geographical locations.** Leading cloud service providers have established data centres worldwide. However, it is unlikely that any provider will be able to establish data centres in every country and administrative region [5]. Many applications have legislative requirements as to where data is stored. Thus a data centre within a region of countries may not be enough, and application developers will need fine-grained control (specific country or state) as to where resources are positioned. Only by utilizing multiple clouds can one gain access to so widely distributed resources and provide well performing and legislation compliant services to clients.
- **Better application resilience.** During the past several years, there have been several cases of cloud service outages, including ones of major vendors [11, 12, 13, 14]. The implications from one of Amazon's data centres failure were very serious for customers who relied on that location only. In a post-mortem analysis Amazon advised their clients to design their applications to use multiple data centres for fault tolerance [11]. Furthermore in Berkeley's report on cloud computing Armbrust et al. emphasise that potential unavailability of service is the number one inhibitor to adopting cloud computing [15]. Thus they advise for the use of multiple providers. Besides fault tolerance, using resources from different providers acts as an insurance against a provider being stopped because of regulatory or legal reasons as well.
- **Avoidance of vendor lock-in.** By using multiple clouds and being able to freely transit workload among them, a cloud client can easily avoid vendor lock-in. In case a provider changes a policy or pricing that impact negatively its clients, they could easily migrate elsewhere.

In essence, the main value of an Inter-Cloud environment for cloud customers is that they can diversify their infrastructure portfolio in terms of both vendors and location. Thus they could make

their businesses more adaptable to vendors' policy and availability changes and easily expandable in new legislative regions.

Cloud service providers may also have significant incentives from participating into an Inter-Cloud initiative. A paramount idea of cloud computing is that a cloud service should deliver constant availability, elasticity and scalability to meet the agreed customers' requirements [4]. A cloud provider should ensure enough resources at all times. But how much is enough? Workload spikes can come unexpectedly and thus cloud providers need to overprovision resources to meet them. Another issue is the huge amount of data centre power consumption [1, 16]. Keeping an excess of resources in a ready to use state at all times for coping with unexpected load spikes leads to increased power consumption and cost of operation. Cloud providers' benefits can be summarized as follows:

- **Expand on demand.** Being able to offload to other clouds a provider can scale in terms of resources like cloud-hosted applications do within a cloud. A cloud should maintain in a ready to use state enough resources to meet its expected load and a buffer for typical load deviations. If the workload increases beyond these limits, resources from other clouds can be leased [5].
- **Better SLA to customers.** Knowing that even in a worst case scenario of data centre outage or resource shortage the incoming workload can be moved to another cloud, a cloud provider can provide better Service Level Agreements (SLA) to customers.

However, achieving all these benefits for both cloud providers and clients should be done without violating applications' requirements. Appropriate application brokering (consisting of provisioning and scheduling) should honour the requirements in terms of performance, responsiveness and legal considerations. Existing approaches to achieve this vary in terms of architecture, mechanisms and flexibility.

In this work we investigate and classify Inter-Cloud environments and application brokering mechanisms. We focus on identifying and analysing the coarse-grained requirements and the state of the art in Inter-Cloud brokering of distributed applications. Based on this we perform analysis of the status quo and identify trends and open issues in the area. To the best of our knowledge this novel area of research has not been systematically surveyed before.

Since the area of Inter-Clouds is novel and there is ambiguity about some of the terms in Section 2 we discuss and define the main ones. In Section 3 we motivate and introduce an architectural taxonomy of existing Inter-Cloud developments. In Section 4 we classify existing approaches for brokering applications across clouds. In Section 5 we classify existing distributed applications, and for every major class of applications we investigate what are the requirements for Inter-Cloud brokering. In Section 6 we review 20 major developments in the area fitting them into the previous taxonomies and discussing their capabilities to facilitate Inter-Cloud application brokering. Section 7 provides an analysis of the state of the art. The final Section 8 concludes the study and defines avenues for future work.

2. DEFINITIONS

Cloud computing is a novel area of research and still faces certain terminological ambiguity. The area of Inter-Clouds is even newer and many works in the area use several terms interchangeably. In this section we elaborate on their meaning.

Inter-Cloud computing has been formally defined as [17]:

“A cloud model that, for the purpose of guaranteeing service quality, such as the performance and availability of each service, allows on-demand reassignment of resources and transfer of workload through a *[sic]* interworking of cloud systems of different cloud providers based on coordination of each consumers requirements for service quality with each providers SLA and use of standard interfaces.”

In the rest of this work we will adhere to this definition. The seminal works on Inter-Clouds by Buyya et al. [5] and Bernstein et al. [6] also implicitly express similar definitions. Buyya et

al. emphasize the just-in-time, opportunistic nature of the provisioning within an Inter-Cloud that allows for achieving QoS and QoE (Quality of Experience) targets in a dynamic environment [5]. The term *Cloud Fusion* has been used by Fujitsu Laboratories to denote a similar notion [18].

Note that this definition is generic and does not specify who is initiating the Inter-Cloud endeavour - the cloud providers or the clients. Also it does not specify whether cloud providers collaborate voluntarily to form an Inter-Cloud or not. Two other terms are used throughout the related literature to differentiate between these - *Federation* and *Multi-Cloud*. A Federation is achieved when a set of cloud providers voluntarily interconnect their infrastructures in order to allow sharing of resources among each other [19, 20, 8]. The term Multi-Cloud denotes the usage of multiple, independent clouds by a client or a service. Unlike a federation, a multi-cloud environment does not imply volunteer interconnection and sharing of providers' infrastructures. Clients or their representatives are directly responsible for managing resource provisioning and scheduling [19]. The term *Sky Computing* has been used in several publications with similar meaning [7, 21]. Both federations and multi-clouds are types of Inter-Clouds. We discuss them further in Section 3.

Another term used in the related literature is *Hybrid Cloud*. It has been defined as a composition of two or more different cloud infrastructures - e.g a private and a public cloud [3]. Thus a hybrid cloud is a type of a Multi-Cloud that connects miscellaneous clouds in terms of their deployment models. Often hybrid clouds are used for *cloud bursting* - the usage of external cloud resources when local ones are insufficient.

Throughout the literature, the term *Inter-Cloud broker* has been used with different meanings. In most cases it means a service that acts on behalf of the client in order to provision resources and deploy application components [5, 19, 22]. We adhere to this general idea and define an *application broker* as an automated entity with the following responsibilities:

- Automatic resource provisioning and management across multiple clouds for a given application. Typically this would include allocation and deallocation of resources (e.g. VMs and storage).
- Automatic deployment of application components in the provisioned resources.
- Scheduling and load balancing of the incoming requests to the allocated resources.

3. ARCHITECTURAL TAXONOMY

By definition Inter-Cloud computing is an endeavour which implies interconnecting multiple cloud providers' infrastructures. The extent to which providers would voluntarily lend their infrastructure within an Inter-Cloud depends on the political and financial incentives they have to do so. Figure 2 depicts how cloud infrastructures can be classified based on their ownership.

On the first level we differentiate between *Governmental* and *Private* cloud infrastructures. These can be described as:

- **Governmental** - owned and utilized by a government or non-profit institution. Examples for this are science community clouds like Australia's National eResearch Collaboration Tools and Resources (NeCTAR) [23] and Canada's Cloud-Enabled Space Weather Modelling and Data Assimilation Platform (CESWP) [24].
- **Private** - owned by a private organization.

Private clouds can be further classified as:

- **Cloud portfolio** - when the cloud is a part of a portfolio of clouds belonging to the same organization. Examples for this are multiple private clouds belonging to a corporation.
- **Independent** - separate cloud infrastructure that is not a part of a portfolio of clouds.

Given that classification we argue that *Independent* private clouds are less likely to participate voluntarily in an Inter-Cloud initiative. Such cloud providers will be reluctant to scale/transit their workload in the data centres of their competitors. Also, such providers may not be willing to provide access through unified APIs to their services in a federated market place, since that would

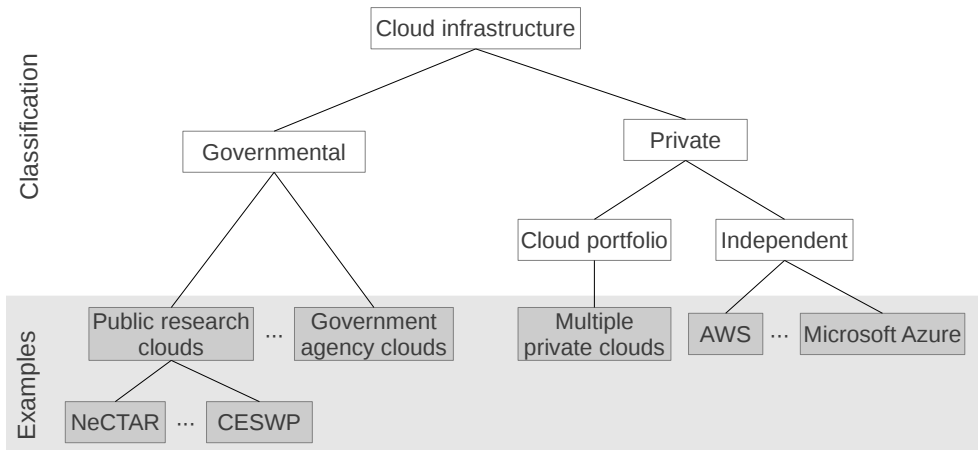


Figure 2. Classification of cloud infrastructures

allow their customers to migrate easily and dynamically to competitors. This can be achieved by using specialized third party services and application programming interfaces (APIs), which will be discussed in details later.

For example despite their data centre outages leaving customers without access to services for substantial periods of time, none of the leading commercial providers (like Amazon, Google and Microsoft) has announced plans to utilize external cloud resources to avoid future outages.

On the other hand *Governmental* clouds are very likely to participate voluntarily within an Inter-Cloud among each other since that could benefit the quality of the overall public service. Similarly *portfolio clouds* are likely to form an Inter-Cloud initiative among each other since they are not directly competing with each other and have clear incentives to collaborate.

Based on this observation we can broadly classify Inter-Clouds as:

- **Volunteer federation** - when a group of cloud providers voluntarily collaborate with each other to exchange resources. As identified this type of Inter-cloud is mostly viable for governmental clouds or private cloud portfolios.
- **Independent** - when multiple clouds are used in aggregation by an application or its broker. This approach is essentially independent of the cloud provider and can be used to utilize resources from both governmentally and private clouds. Another term used for this is *Multi-Cloud*.

From architectural perspective *Volunteer federations* can be further classified as:

- **Centralised** - in every instance of this group of architectures there is a central entity that either performs or facilitates resource allocation. Usually this central entity acts as a repository where available cloud resources are registered, but may also have other responsibilities like acting as a market place for resources.
- **Peer-to-Peer** - in the architectures from this group clouds communicate and negotiate directly with each other without mediators.

Independent Inter-Cloud developments can be further classified as:

- **Services** - application provisioning is done by a service which can be hosted either externally or in-house by the cloud clients. Most such services include broker components in themselves. Typically application developers specify an SLA or a set of provisioning rules and the service performs the deployment and execution in the background, in a way respecting these predefined attributes.
- **Libraries** - often custom application brokers that directly take care of provisioning and scheduling application components across clouds are needed. Typically such approaches make use of inter-cloud libraries that facilitate the usage of multiple clouds in a uniform way.

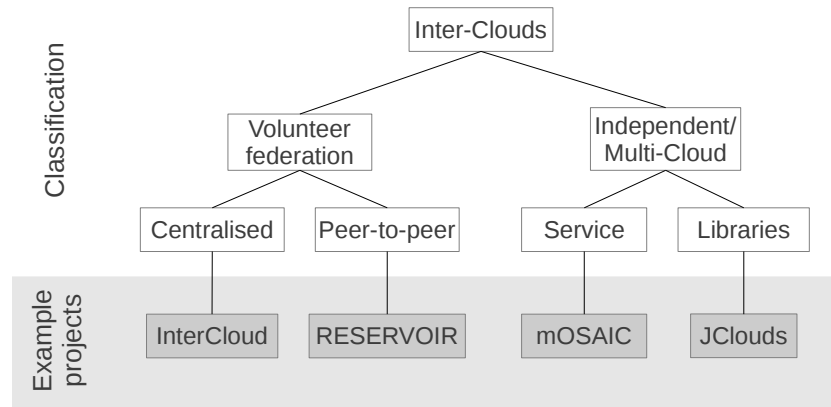


Figure 3. Architectural classification of interclouds

The whole taxonomy of developments is depicted in Figure 3. Figure 4 depicts the architectures from the taxonomy. In Section 6 we discuss in details many examples of developments in all these areas. Note that the discussed herein classifications are orthogonal to the general classification of Cloud computing services as Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) as defined by NIST [3]. For example cloud providers within a federation can exchange resources at the infrastructure level (e.g. VMs) but at the same time provide PaaS to clients. Also in theory a multi-cloud service may access IaaS, PaaS or SaaS cloud services on behalf of its clients.

4. TAXONOMY OF INTER-CLOUD APPLICATION BROKERING MECHANISMS

There are several mechanisms for implementing application specific brokering as depicted in Figure 5. At the first level we differentiate as to who is responsible to provide implementation of the application broker. Brokers using *Externally managed* mechanisms usually are not hosted in-house and are a part of the system entities that facilitate the Inter-Cloud. In the case of *Multi-Cloud Services*, application brokers are often part of the service providing access to the set of clouds. In the case of *Volunteer Federations*, application brokering is implemented either in a centralized entity or by the cloud providers. In essence *Externally managed* brokers are transparent to the application developers and provide some “hooks” for application specific logic.

Based on the way application specific logic is specified we can further classify *Externally managed* brokering mechanisms as:

- **SLA based** - application developers specify the brokering requirements in an SLA in the form of constraints and objectives. The cloud provider or the Inter-Cloud service acting on behalf of the client decides on brokering approach honouring the specified SLA.
- **Trigger-Action** - the application developers specify a set of triggers and associate one or more actions to each of them. A trigger becomes active when a predefined condition considering the externally visible application performance indicators becomes true. An action is executed when a correspondent trigger becomes active. Actions usually include scale up/down or other provisioning activities. For example a trigger may become active if the number of active TCP/IP sessions becomes more than 50, or if the memory consumption of an allocated VM exceeds 512MB. An associated action may be the allocation of a new VM.

The main benefit of the *SLA based* brokering approaches is that they are completely transparent to the application developers. The provider or the service takes care of the provisioning behind the scenes.

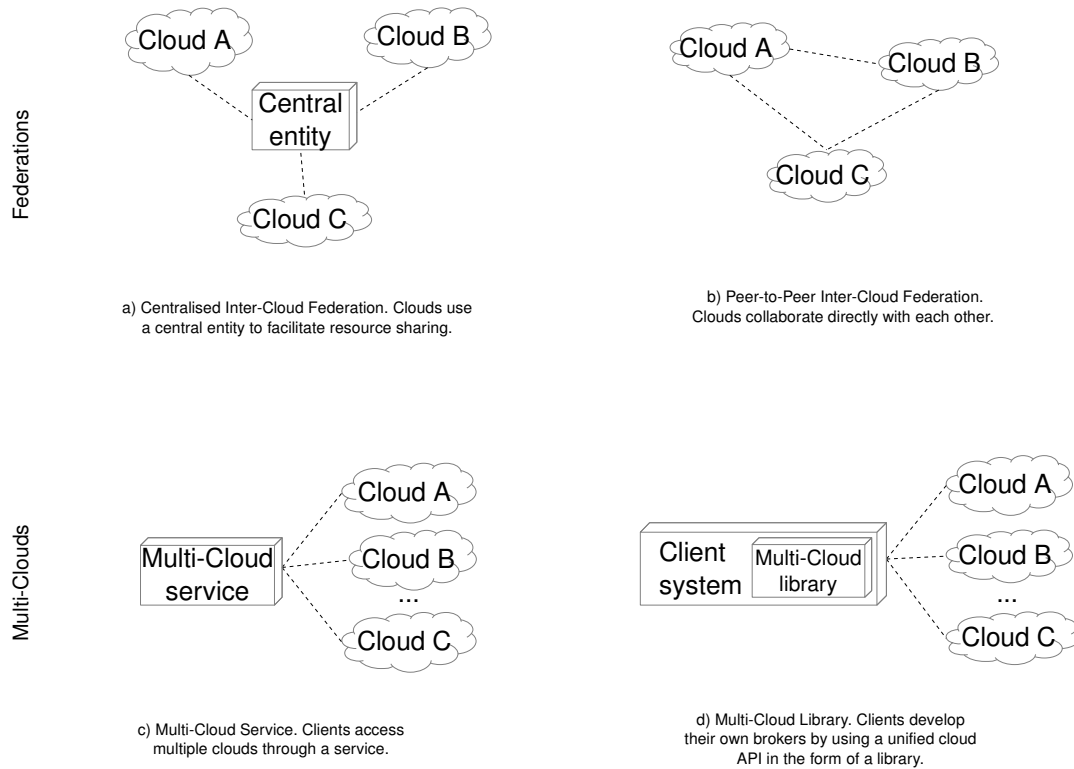


Figure 4. Inter-Cloud developments' architectures

However, in *SLA based* brokering clients do not have direct control on how their applications are provisioned across clouds. Thus there needs to be a certain level of trust between the two sides. Also, in order to specify the provisioning requirements of an application one needs mature SLA specification formalisms and services. In a report from The Cloud Standards Customer Council (CSCC), it was emphasised that SLA contracts offered by current cloud providers are immature [25]. Often clients are offered only non-negotiable standard SLA contracts thus limiting their ability to define application specific clauses. Most such contracts only specify performance related clauses and do not allow for provisioning restrictions - e.g. which location to use for data storage. Thus the adoption of *SLA based* brokering approaches depends on the advancements of providers' and mediators' SLA offerings.

The *Trigger-Action* approach is less transparent than the *SLA based* one, since application developers need to specify the exact scalability and provisioning rules. This gives a more fine grained control about how the application behaves.

The *Directly managed* brokering mechanisms are mostly used when there is no mediator between the application and the set of utilized clouds. *Directly managed* brokers are hosted separately and need to keep track of the performance characteristics of the application themselves. It is the responsibility of the application developers to develop such brokers in a way that meets the availability and dependability requirements.

5. APPLICATION CENTRIC PERSPECTIVE TO INTER-CLOUDS

Clouds as a deployment environment are general purpose and cover the whole spectrum of distributed applications. Cloud providers have always delivered computing resources to enterprises. Thus many data base centric enterprise applications are deployed within clouds. Being an

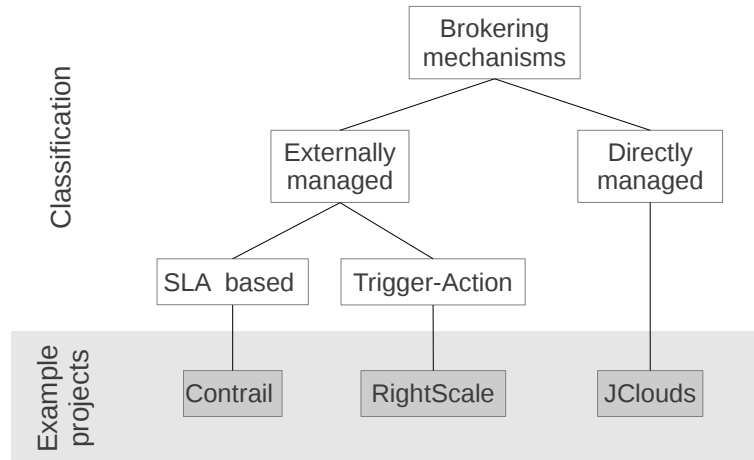


Figure 5. Application brokering mechanisms

inherently distributed environment, clouds are also suitable for standard Grid and Cluster job-based applications. Research community clouds like Australia's NeCTAR [23] and Canada's CESWP [24] have made the use of clouds for resource intensive jobs apparent, though there are still concerns about the worse performance of cloud clusters compared to physical ones as reported by Jackson et al. [26]. Developments like EC2 Cluster Compute Instance [27] are supposed to mitigate such issues. It is logical to expect that the same spectrum of applications will be targeted for the Inter-Cloud.

In this section we perform a taxonomic analysis to identify classes of distributed applications with similar characteristics. Then we continue to identify the common non-functional requirements of these application classes with respect to the Inter-Cloud environment in which they are deployed.

5.1. Taxonomy of Inter-Cloud Applications

Figure 6 depicts the taxonomy of typical distributed applications deployable in Inter-Cloud environment that will be discussed from now on. At the first level we differentiate between *Batch processing* and *Interactive* applications. *Batch processing* applications allow the users to submit and execute jobs, which then run to completion without further user input. Thus they can also be thought of as job-based applications. *Batch processing* applications can be further classified as allowing *Singular* or *Periodical* jobs.

Singular jobs are executed only once, unless they are rerun by the users or automatically rescheduled upon failure. This branch of the taxonomy represents the typical Grid and Cluster resource intensive applications. Such applications are used by research, industry and military organizations to solve optimization models, build complex simulations etc. Most of the applications in this branch fall into the High Performance Computing (HPC), High Throughput Computing (HTC) or Many-task Computing (MTC) categories. Raicu et al. defines these three types of applications and discusses their differences and similarities [28]. *Scientific workflows* (further discussed by Barker and Van Hemert [29]) are also a kind of *Singular* jobs, though they are composed of multiple subjobs/tasks, since they appear to the user as a single unified job.

Singular jobs typically require fast connection between the processing nodes and are less likely to be deployed across clouds. Exceptions to this are HTC applications, where independent long running tasks may be scheduled across clouds. Another reason for scheduling a job in multiple clouds is fault tolerance - if a job fails in one cloud environment it may succeed in another.

Periodical jobs are repeatedly executed over a period of time. Most of them are *Data centric* and perform long running tasks over huge enterprise data bases. Periodic Extract Transform Load (ETL) jobs in Data warehouses, reporting jobs and Big Data analytical jobs are examples of this. *Data centric* periodical jobs are of great significance for enterprises with large scale information systems.

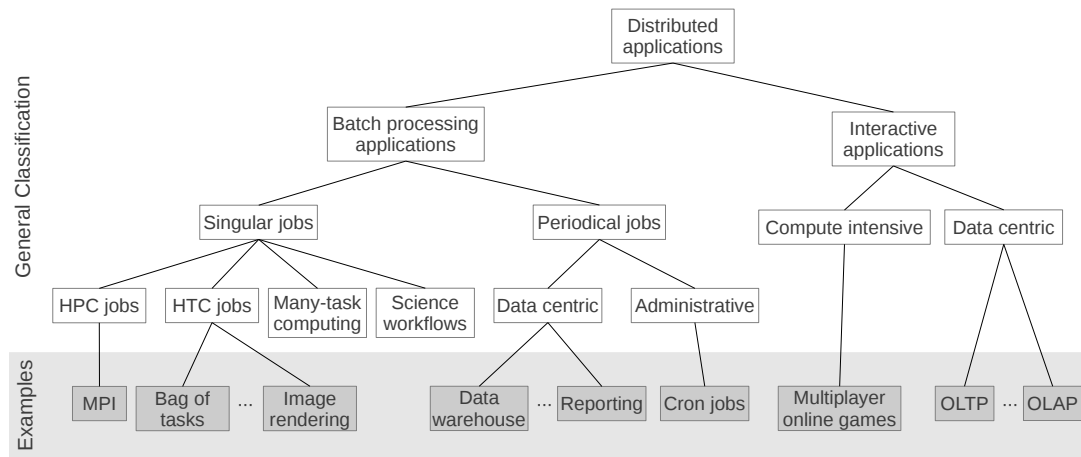


Figure 6. Classification of distributed applications

They are often scheduled to run at nights or weekends to ensure smooth business operation during business hours. *Administrative* periodical jobs are relatively simple and take care of maintaining the system in a healthy and running state. Examples are scripts that periodically consolidate log files from all nodes or release unneeded resources across nodes.

Data Centric Periodical jobs typically need to be executed close to where the corresponding data is stored. Thus Inter-Cloud scheduling and provisioning are sensible when the persistent data is dispersed in multiple clouds.

Interactive applications are also known as *Online* applications. Unlike the *Batch processing* ones they imply constant interaction and input from the user. Most interactive distributed systems are *Data centric*. That is their main goal is to facilitate user access to a persistent storage (most often a relational database). Typical examples are Online Transaction Processing (OLTP) applications. Another group of *Interactive* applications are the *Compute Intensive* ones. Examples for such are multilayer online games.

Unlike *Batch processing* applications *Interactive* ones need to be constantly available and thus would benefit the most from using multiple clouds. Also many online applications serve users from around the world and thus would benefit from the geographical diversity of an Inter-Cloud's data centres.

5.2. Requirements for Inter-Cloud Environments

As discussed the main benefit from the clients' perspective of an Inter-Cloud environment is the diversification in terms of vendors and locations. It is however important that this is done without violating the non-functional application requirements. Not all Inter-Cloud environments allow for such control. Thus in the rest of this section we define several requirements for Inter-Cloud environments and discuss for which of the main classes of applications these are important. Table I summarizes the discussion.

Data Location Awareness

Ideally the persistent data and the processing units of an application should be in the same data centre (even on the same rack) and should be connected with a high speed network. If they reside on remote clouds the performance penalty could be grave.

This consideration is especially important for interactive applications and periodical jobs using huge data bases. Actually in this case the data base considerations are becoming a driving factor in Inter-Cloud brokering. The database often becomes the performance bottleneck of a distributed enterprise application. Additional approaches like distributed caching and sharding are often used to mitigate to some extent the performance issues of traditional databases [30].

In recent years there has been a trend to move away from standard relational databases to the so-called NoSQL and NewSQL ones. There has been significant amount of developments in these fields (Cattel reports on more than 20 projects [31]). The term NoSQL denotes a broad range of non-relational database developments. In essence the NoSQL approach aims at balancing between consistency and partition tolerance following the result of the famous CAP theorem [32, 33], while NewSQL approaches keep to standard relational approaches but discourage or ban performing certain inefficient operations [31].

Many enterprise systems will need to use several types of data sources simultaneously. For example payment information may be stored in a transactional relational database to ensure consistency, but other data like catalogues of products may be stored in a NoSQL storage for better performance. This phenomenon has been termed *Polyglot persistence* by several practitioners [34, 35].

But why is this important in terms of Inter-Cloud brokering? An inter-cloud broker of a data-centric application is essentially responsible for allocating resources on multiple clouds and scheduling incoming requests to these clouds appropriately. Developers need the flexibility to implement brokering policies considering the structure and the location of distributed persistent data and cache servers. Thus a successful broker should be well integrated with its application and should get feedback from it regarding the structure and location of data.

Most Singular job-based applications are compute intensive programs and thus avoid substantial I/O operations. Some of them however work on datasets that have been extracted in advance for example by conducting experiments. In such cases the data is usually stored in standalone persistent storage - e.g. relational database or a data file. Typically either the data is replicated to the node running the job or the job is scheduled on a node near the data. The latter is preferred when the dataset has substantial size. There has been substantial work in the last decades on data aware scheduling of singular jobs in Grids and it has been well summarized by Dong and Akl [36]. In order to apply these approaches in an Inter-Cloud environment the location of the data (or its replicas) is needed.

Geo-location Awareness

Besides data-base considerations the location of the incoming requests is also important to consider when brokering interactive applications. Ideally requests should be scheduled near the geographical location of their origin in order to achieve better performance. This is not usually considered when brokering jobs, since the users submit the jobs only once and do not interact with the system until they finish. In interactive systems however, network bandwidth latency caused by geographical distances may hurt the user experience significantly.

Pricing Awareness

A common consideration for all types of applications deployed in multiple clouds is the pricing. Different providers have different pricing policies and mechanisms and minimizing the overall hosting price is a non-trivial task. An application broker would need detailed and up to date information about providers' prices and policies in order to perform fiscally efficient provisioning.

Legislation/Policy Awareness

For some applications the application broker should take into account legislative and political considerations upon provisioning and scheduling. For example such a broker could avoid placing part of the data outside a given country or can avoid using cloud services of a specific vendor.

This is a typical requirement in both interactive and batch processing data centric applications. In rare cases this can be a requirement for singular job applications as well - e.g. when performing research on a dataset of medical records.

Local Resources Awareness

Another consideration which is common to all application types is the usage of local in-house resources with higher priority than external ones. That is cloud bursting should be allowed only if

Table I. Typical Inter-Cloud brokering requirements

Awareness	Job based		Interactive applications	
	Singular Jobs	Periodical Jobs	Compute Intensive	Data centric
Data Location	✓	✓		✓
Geo-location			✓	✓
Pricing	✓	✓	✓	✓
Legislation/Policy	✓	✓		✓
Local Resources	✓	✓	✓	✓

the local resources are insufficient or unsuitable in terms of geographical location, proximity to data or operational costs.

6. STATE OF THE ART IN INTER-CLOUDS

In this section we summarize several state-of-the-art Inter-Cloud developments. They were identified after an extensive analysis of the related literature and include both academic and industry projects. Each of the following subsections discusses the projects that fall into one of the architectural groups introduced in Section 3. Besides a technical summary for each project we also discuss where it fits within the introduced taxonomies and how it addresses the requirements from Section 5.

6.1. Centralised Federated Inter-Clouds

InterCloud

The *InterCloud* [5] project developed at the University of Melbourne is one of the first initiatives in the field. It extends previous efforts from the *InterGrid* project to allow the sharing of resources across cloud providers [37]. The proposed architecture is centralised and is built around a central entity called *Cloud Exchange* (CEx). In essence CEx acts like a marketplace where clouds can sell resources. The buyers may be other clouds or application brokers. Thus the architecture is clearly market oriented and facilitates pricing aware application brokering.

Each cloud data centre participating in an *InterCloud* federation needs to have an agent called *Cloud Coordinator* (CC) installed. *Cloud Coordinators* manage the federation memberships of the clouds by communicating with CEx on their behalf [5]. An architecture of an extensible *Cloud Coordinator* has been further discussed by Calheiros et al. [38].

To serve as a federation wise marketplace the *Cloud Exchange* (CEx) maintains an information registry of the clouds' resources. The *Cloud Coordinators* of the participating providers periodically update their details within this information registry [5]. Geographical location of resources can be maintained within CEx and thus location aware brokering is possible. Brokering in *InterCloud* can be either *SLA based*, when a cloud provider brokers on behalf of the client, or *Directly managed* when clients directly buy and use resources from CEx.

Contrail

The architecture of the European project *Contrail* [39] is built around a centralised composite entity that acts as a single entry point to a federation of cloud providers. It is responsible for periodically observing the states of the cloud providers and facilitating a federation wise SLA. It also provides single sign on, so that users need to authenticate only once in order to work with the entire federation. A special architectural component called *Federation Runtime Manager* (FRM) is dedicated to mapping users' requests to cloud resources. It implements cost and performance

optimization heuristics and ideally should have access to the geographical location and other meta information about every cloud provider [39]. Application brokering is achieved by specifying a detailed application SLA. It is the responsibility of the FRM module to provision in accordance with the SLA and to minimize the costs. However, the documentation is not specific whether users are allowed to specify geographical, legislative and data location constraints in the SLA.

The *Adapters Layer* architectural component constitutes of adapters for every cloud provider in the federation. The adapters facilitate the communication between the federation management components and the clouds. The adapters can be classified as:

- **Internal adapters** - for clouds running the Contrail software. These are called Contrail clouds. Contrail clouds allow for the federation management components to reserve and configure their resources [39].
- **External adapters** - for clouds that do not run the Contrail software.

When using *External adapters* the cloud providers themselves are agnostic of the federation - they do not voluntarily participate in it. Thus in terms of the presented here architectural taxonomy a Contrail federation using *External adapters* is considered a Multi-Cloud and will be discussed in a later section. On the other hand a Contrail federation using *Internal adapters* is considered a centralised federation. In other words *Contrail* supports both types of architectures. It even supports a hybrid architecture that utilizes both clouds participating voluntarily within a federation and federation agnostic clouds.

Dynamic Cloud Collaboration (DCC)

In the centralised federation architecture *Dynamic Cloud Collaboration* (DCC) the central entity that facilitates the federation is one of the clouds called *primary cloud provider* (pCP). This is the first cloud provider in the federation - the one that actually established it [40, 41]. The other cloud providers are called *collaborating clouds*. The primary cloud (pCP) maintains a registry of the services of the collaborating clouds. Application brokering is done via SLA contract with pCP. Cloud clients submit requests to the pCP, which based on the requests' characteristics allocates resources within the federation. It has not been specified whether clients are allowed to declare requirements about the geographical location of the allocated resources. However, there has been work on the facilitation of a cloud market place where auctions for resources are held [41].

Federated Cloud Management (FCM)

The *Federated Cloud Management* (FCM) architecture relies on a generic repository called *FCM Repository* to store virtual appliances for all federated services [42]. It is replicated to the native repositories of the different IaaS providers. Clients interact only with the *Generic Meta-Broker Service* (GMBS) describing the requested service and as far as they are concerned further provisioning and scheduling is transparent [42].

For every IaaS provider in the architecture there is a correspondent broker called *CloudBroker* managing the allocation and deallocation of VMs and dispatching incoming application calls to appropriate VMs. GMBS has access to the *FCM Repository* and can communicate with the *CloudBroker* components of the federated clouds. When GMBS receives a request from a user it performs matchmaking between the request and an appropriate *CloudBroker*. The matchmaking is based on information from the *FCM Repository* and runtime metrics provided by the *CloudBrokers*.

Each *CloudBroker* maintains an internal queue of incoming application calls and a separate priority queue for every virtual appliance. VM queues represent the resources that can serve a virtual appliance related service call. The priority of each VM queue is based on the currently available requests in the queue, their historical execution times, and the number of running VMs. Based on the VM queues the *CloudBroker* needs to perform appropriate VM creation and destruction. A *CloudBroker* also handles the aforementioned queue of incoming calls by redirecting them to the VMs created as a result of the management of the VM queues.

Application brokering in FCM is done transparently to the client. In the definition of the architecture nothing has been said about user-level control over the location of the used resources and how cost optimization can be achieved [42]. We could speculate that location specific

requirements can become a part of the SLA between the clients and GMBS. In a separate work Kecskemeti et al. extend the FCM approach to facilitate self-adaptable and autonomous management of the federation [43]. One of their goals is to achieve resource optimization (and consequently costs optimization) without violating the SLAs. However, this optimization concerns the resource utilization of the whole federation and does not necessarily lead to cost optimizations for all federation's clients.

6.2. Peer-To-Peer Federated Inter-clouds

RESERVOIR

The *Resources and Services Virtualization without Barriers* project (RESERVOIR) is a European project which extends previous research on interconnecting Grids. Its architecture does not feature a central entity and is peer-to-peer - clouds communicate directly with each other to negotiate resource leasing. The usage of multiple clouds is facilitated through *Claudia* - an abstract layer for execution of services on top of a cloud federation [44].

Custom application brokering in RESERVOIR can be achieved through elasticity rules of the type *Trigger-Action* [45]. Developers can also specify how their applications scale in a declarative way. This is done by specifying the SLA of the application in terms of performance objectives (e.g. response time) and a control strategy characteristic (e.g. number of virtual machines). RESERVOIR then creates an approximate elasticity behavioural model that optimizes the control strategy characteristic without violating the SLA constraints [45].

RESERVOIR requires that all deployed applications should be agnostic of the hosting data centre location, thus allowing for transparent deployment anywhere within the federation. The clients and their application brokers have no control over the selected hosting cloud [45]. RESERVOIR can be considered to be pricing aware, since the price of the used resources could be optimized if set as a control strategy characteristic, as explained earlier.

Open Cirrus

Open Cirrus is a test bed for distributed systems research and federates several research data centres across the globe. Open Cirrus is not an Inter-Cloud environment per se, since it allows users to work directly with the hosts besides utilizing virtualized resources [46, 47]. Publications about the project do not give much details about the middleware involved in it. It is known that the test bed runs the experimental cluster management software Tashi [48], the Hadoop framework [49] and a custom physical resources management system called Zoni [46].

The Open Cirrus environment has been designed to be data location aware. Tashi and the location metadata provided by the Hadoop Distributed File System (HDFS) are used to schedule computing tasks on the nodes where the correspondent persistent data resides [46]. However, in the publications on the topic nothing has been said about location awareness when using datasets other than HDFS files (e.g. relational data base). Also it has not been stated if users can control the location of the used resources and if they have access to pricing information if pricing is at all present in this research test bed.

OPTIMIS

The OPTIMIS toolkit requires that OPTIMIS software agents are deployed within cloud providers and application brokers. These agents communicate with each other to implement Inter-Cloud provisioning.

One of the agent components is the *Deployment Engine* (DE). It is responsible for the discovery and negotiation with suitable clouds for hosting a particular service. Firstly a set of suitable clouds meeting some predefined conditions are identified and the *service manifest* (an SLA template) is sent to each of them. The cloud providers answer either with a rejection to accept the service or a deployment offer. DE selects the best offer based on the quantitative (e.g. cost) and qualitative (e.g. some measurement of trust) aspects of the offer. DE is also responsible for initiating the deployment of the service within the selected cloud by providing the appropriate VM images that constitute the

needed service. After the deployment of the service, the *Service Optimizer* module is responsible for continuously monitoring the service parameters for SLA violations [19].

On the side of the contacted by the DE cloud the *Admission Controller* (AC) is responsible for either making an offer or rejecting the request. The decision is based on the current workload of the cloud, the requested resources and an evaluation of the potential profit. Allocation of resources for the provided VMs is done by the *Cloud Optimizer* (CO) [19].

Application brokering can be implemented by configuring the DE components of the application broker or the hosting cloud provider. During the selection process DE considers the prices of the deployment offers together with other metrics including trust, risk and energy impact numerical assessments. The exact algorithm for this selection and how configurable it is have not been disclosed. Also it has not been stated whether DE considers the geographical location of the clouds and the persistent data the provisioned service uses. It has only been mentioned that juridical and political restrictions can be specified and then honoured by the respective DE [19].

The OPTIMIS toolkit supports peer-to-peer federation, when cloud providers communicate directly with each other transparently to their clients. It also supports Independent Inter-Clouds (Multi-Clouds), which will be discussed in a successive section.

Arjuna Agility

Arjuna Agility [50] is a commercial framework for establishing Inter-Cloud federations. It is mostly tailored for federations of in-house data centres but can also facilitate cloud bursting (usage of public clouds) if the demand increases beyond in-house resource capabilities. Each federation site needs to install an Agility software agent that governs the interaction with the other sites [51]. Each site has its own policy regarding resource sharing and can define what resources in terms of hardware and software are shared. Being targeted mostly at in-house cloud federations, Arjuna Agility addresses provider specific problems like reducing the power consumption [52, 53]. To this point it does not feature cost optimization. Priority usage of local resources is addressed as a data centre borrows resources only if it can not meet its own demands. Provisioning decisions are governed by provisioning policies set by an administrator. They are federation specific, not application specific [51].

Global Inter-Cloud by Bernstein et al.

Bernstein et al. envision a worldwide federation of cloud providers, rather than separate small scale federations [54]. They draw analogies from previous experience in integrating separate systems into large scale utility services - e.g. electricity and phone systems and the Internet. They propose a new Inter-Cloud architecture following some of the main design principles of the public Internet.

In a global Inter-Cloud environment it is important for cloud providers to discover each other and to match their needs for resources. Bernstein et al. propose the usage of a global resource catalogue called *Cloud Computing Resource Catalogue*. It contains information about the shared resources within the federation and should be hosted by several community governed *Intercloud Root* servers. Root servers replicate the catalogue among each other to provide better performance and availability.

Negotiation between providers is facilitated by *Intercloud Exchanges* - distributed servers that allow cloud providers to discover suitable resources. *Intercloud Exchanges* perform match making between cloud providers based on specified preferences and constraints. *Intercloud Exchanges* use the resource catalogue stored on the *Intercloud Roots* to provide a Distributed Hash Table (DHT) suitable for fast querying. After the negotiation is done, cloud providers continue to communicate directly with each other.

The proposed architecture is not centralized since the *Intercloud Roots* and *Exchanges* are distributed and replicated. Thus a failure of any of them can not cause a failure of the federation as a whole.

To facilitate all phases of the described global Inter-Cloud system, each participant should have an entity called *Intercloud Gateway*. These entities allow cloud providers, *Intercloud Roots* and *Exchanges* to communicate with each other using a set of Inter-Cloud protocols and standards. To

date such interoperability protocols and standards have not been widely utilized, though there are already ongoing works in the area [6, 55, 56, 57].

From the clients' viewpoint, application brokering is achieved through specifying appropriate constraints and preferences in the SLA with the cloud provider. The cloud provider should then respect the SLA when submitting requests to an *Intercloud Exchange*. Both private and public clouds can participate within the envisioned global federation. Thus private clouds can consider using local resources before utilizing external clouds. Bernstein et al. envision that cloud providers should be able to specify resource location preferences and constraints on behalf of their clients when negotiating in order to meet legislative and political requirements [54]. Cloud providers could also implement cost optimization policies on behalf their clients, though this has not been discussed in the related literature.

6.3. Multi-Cloud Services

OPTIMIS

Besides federation OPTIMIS also supports Independent Inter-Clouds (Multi-Clouds) [19]. In terms of the OPTIMIS architecture a Multi-Cloud is achieved when clients use their *Deployment Engine* (DE) and *Service Optimizer* (SO) directly to launch and monitor services within multiple cloud providers.

A major drawback here is the need to work with cloud providers that have OPTIMIS agents deployed in their data centres. As discussed often cloud providers would not wish to voluntarily participate in an Inter-Cloud and install such agents. The OPTIMIS vision is to allow for externally developed adapters for such clouds which should facilitate the communication between OPTIMIS agents and OPTIMIS agnostic cloud providers. Such adapters should be developed for every used cloud service provider.

Contrail

Like OPTIMIS, Contrail [39] also supports both federation and independent Inter-Clouds. Alike OPTIMIS, a major drawback of Contrail in terms of supporting independent Inter-Clouds is the need to develop and maintain multiple vendor specific Contrail adapters.

mOSAIC

The *mOSAIC* open source API and platform allow for the development and deployment of applications that use multiple clouds [21]. Unlike most other Inter-Cloud technologies, mOSAIC has some assumptions about the architecture of the deployed application. It is assumed that the application is divided into components with explicit dependencies in terms of both communication and data between them. Also the application architecture must be service oriented (SOA) and must use only the mOSAIC API for inter-component communication. Other types of communication (e.g. direct sockets) are disallowed. For each component application developers must specify the resource requirements in terms of computing, storage and communication. Some resource requirements are specified for the whole application as well - e.g. overall budget [21].

The mOSAIC platform automatically provisions such applications across a set of predefined clouds, without direct involvement from the user. Thus the only way to control the application brokering is through the predefined SLA on performance indicators at component and application level.

Application brokering in mOSAIC is done by a component called *Resource Broker* (RB). It is responsible for the mediation between clients and cloud providers. RB is further composed of a *Cloud Agency* (CA) which is responsible for discovery and negotiation with cloud providers and a *Client Interface* (CI) responsible for requesting additional resources from the *Application Executor* component. The *Application Executor* (AE) component manages the deployment, execution and monitoring of the application within the reserved resources [21]. In this architecture pricing awareness is promoted through the *Cloud Agency* component which takes into consideration and negotiates on the pricing policies of the cloud providers.

STRATOS

STRATOS is a cloud broker service at an early stage of development [58]. The entry point of the system is the *CloudManager*. Clients describe the application topology and requirements in a *Topology Descriptor File* (TDF) and submit it to the *CloudManager*. It contacts the *Broker* component, which determines the optimal initial resource allocation across clouds. The *Broker* uses another architectural component called *Translation Layer* to access miscellaneous clouds through a uniform API. The *CloudManager* and the *Broker* continuously receive monitoring information based on which they take further provisioning decisions.

Application specific brokering is achieved by specifying requirements and policies within the TDF. STRATOS is obliged to honour the terms from the TDF. Thus the TDF can be considered as an SLA document between the client and the STRATOS service. The TDF format is XML based and allows for the specification of deployment topology configuration (in terms of VM images, middleware, storage etc.), constraints, and objectives. The goal of the *Broker* is to optimize the objectives without violating the constraints or breaking the application topology. To build optimizational models the *Broker* needs adequate measurements of the performance characteristics of cloud providers. For this purpose STRATOS utilizes the Service Measurement Index (SMI) [59] and the metrics defined by Garg [60] and Zachos et al. [61].

The cost is a usual candidate for an objective and thus STRATOS can be pricing aware [58]. We could speculate that Geo-location and Legislation/Policy awareness can be promoted via TDF constraints, though this has not been discussed in the related literature. Also the mapping of incoming requests to nodes near the appropriate data persistence storage has not been discussed.

Commercial Cloud Management Systems

Several companies provide paid independent Multi-Cloud services. In essence their features are similar and they compete against each other on the basis of the performance overhead they add and the variety of cloud providers they can integrate with. It is beyond the scope of this work to survey all players in this dynamic market niche and here we only outline the features provided by some of the major companies.

RightScale offers a service for deploying and managing applications across clouds. Users can manage virtual machines on multiple clouds through the RightScale console [62]. Application brokering is achieved through the *alert-action* mechanism, similar to the *trigger-action* mechanism. All RightScale virtual machines have predefined “hooks” which continuously send information back to the RightScale console. This facilitates the check of the alert conditions and the execution of the predefined actions. Actions can define scale up/down policies but can also be administrative in nature (e.g. sending email to the system administrator). As an action a user is allowed to specify in which cloud and location resources should be provisioned. Thus scaling within RightScale can be location aware. Users can add private clouds within the RightScale console to facilitate local resources utilization.

Generally speaking, the services of EnStratus [63], Scalr [64] and Kaavo [65] are comparable to those of RightScale. Naturally there are difference in the pricing, the set of supported cloud vendors and technologies and some terminology. Alike RightScale, they allow users to deploy virtual machines across different public and private clouds. Application brokering is achieved through automated triggers, similar to RightScale’s alerts, which can trigger scale up/down actions.

6.4. Inter-Cloud Libraries

Several Inter-Cloud libraries have been developed in recent years. Examples are the Java library JClouds [66], the Python library Apache LibCloud [67], the Ruby library Apache DeltaCloud [68] and the PHP library SimpleCloud [69]. Another library project at a very early stage of development is Apache Nuvem [70].

All these libraries are designed to abstract the programmers from the differences in the management APIs of clouds and provide control over the provisioning of resources across geographical locations. Such libraries can be used to ease the development of cloud adapters for technologies like OPTIMIS or mOSAIC. By using such libraries application developers can

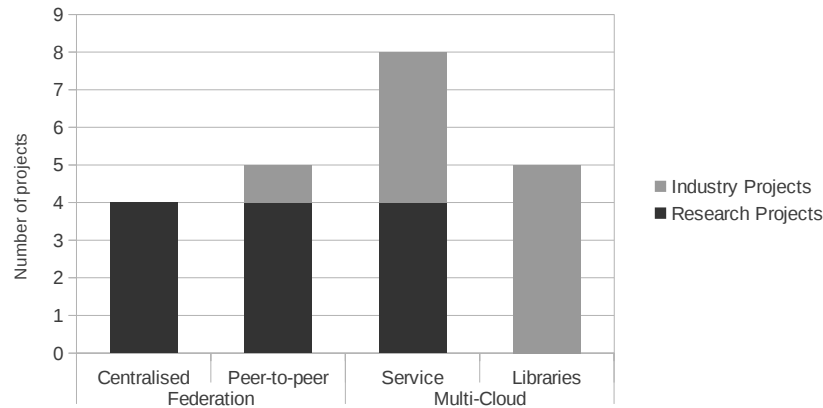


Figure 7. Inter-Cloud projects by architecture

program their own application specific brokers. Such brokers directly manage the underlying cloud infrastructures and thus can meet all of the previously outlined requirements. A major issues with this approach is that developers need to define appropriate deployment and replication of the broker for availability reasons.

7. DISCUSSION

In the current work we have discussed and classified 20 major Inter-Cloud developments, identified after detailed analysis of the related work. These include both academic and industry projects, which are summarized in Table II. Figure 7 outlines how many of them fall into each of the taxonomic groups discussed earlier. The sum of the counts is greater than 20, since some projects support multiple Inter-Cloud topologies.

Most *Multi-Cloud* projects are industry driven. That is they are not research projects supported by academic grants or developed in an academic environment. Exceptions are OPTIMIS, Contrail and mOSAIC co-funded by the European Union and STRATOS which is partially supported by Canada's Natural Sciences and Engineering Research Council (NSERC). Of these only mOSAIC and STRATOS support exclusively a Multi-Cloud, and the other two support Inter-Cloud federations as well. On the contrary, almost all Inter-Cloud Federation projects are visionary research projects. The only exceptions is Arjuna Agility, used to build in-house Inter-Cloud federations.

This speaks for the fact that currently there is a market demand for Multi-Clouds and the technologies to facilitate them are available. As discussed the predominant use of *Multi-Clouds* is to provide cloud agnostic access to multiple competing *Independently owned* clouds without their collaboration and knowledge. Such mediating services and libraries are especially useful for small and medium sized businesses that want to deploy applications in multiple public cloud environments for better availability, flexibility and responsiveness. Thus there is already competition between the providers in this market niche.

On the contrary almost all federation initiatives are research projects at an early stage of development and adoption. This is because of the many open issues that need to be addressed with respect to provisioning resources and scheduling application components on behalf of the clients.

The majority of the discussed developments take an *SLA based* approach to Inter-Cloud application brokering. These projects try to make the Inter-Cloud transparent to its clients, but as discussed the SLA based approach currently meets series of shortcomings. Thus all of them are research projects at an early stage of development - see Figure 8. The direct approach is the most flexible but is also the hardest to work with from the clients' perspective, since clients would need to program their own application brokers. The *Trigger-Action* approach is used by both federations and Independent Inter-Cloud services. It combines the declarative nature of the SLA approach and

Table II. Summary of Inter-Cloud projects

Project	Type, Organization	Architecture	Brokering Approach	Application Type	Awareness
InterCloud	Research project of University of Melbourne	Centralised federation	SLA based and Directly managed	Singular Jobs	Geo-location, Pricing
Contrail	Private and public European research organisations Funded by EU	Centralised federation and Independent Service	SLA based	Singular Jobs	Pricing
Dynamic Cloud Collaboration (DCC)	Academic research project supported by South Korean research funds.	Centralised federation	SLA based	Singular Jobs	Pricing
Federated Cloud Management (FCM)	Academic research project supported by EU funds.	Centralised federation	SLA based	Singular Jobs	Pricing
RESERVOIR	Private and public European research organisations Funded by EU	Peer-to-peer federation	SLA based and Trigger-Action	Singular Jobs	Pricing
Open Cirrus	Research testbed by academic and industry partners. Partially funded by US NSF.	Peer-to-peer federation	Directly managed	Singular Jobs	Data location
OPTIMIS	Private and public European research organisations Funded by EU	Peer-to-peer federation and Independent service	SLA based	Singular Jobs, Periodical Jobs, Compute and Data Intensive Interactive application	Pricing
Arjuna Agility	Commercially owned	Peer-to-peer federation	Trigger-Action	Singular Jobs, Periodical Jobs, Compute and Data Intensive Interactive application	Local resources
Global Inter-Cloud by Bernstein et al.	Publications are by people from miscellaneous companies - CISCO, Huawei Technologies, EMC Corporation	Peer-to-peer federation	SLA based	Singular Jobs, Periodical Jobs, Compute and Data Intensive Interactive application	Data location, Local resources
mOSAIC	Private and public European research organisations Funded by EU	Independent service	SLA based	Singular Jobs, Periodical Jobs, Compute and Data Intensive Interactive application	Pricing
STRATOS	York University. Supported by Canada's NSERC funds, Amazon and CA Inc.	Independent service	SLA based	Singular Jobs, Periodical Jobs, Compute and Data Intensive Interactive application	Geo-location, Pricing, Legislation/Policy and Local resources
Commercial Cloud Management Systems (RightScale, EnStratus, Scalr, Kaavo)	Commercially owned	Independent service	Trigger-Action	Singular Jobs	Geo-location, Data location, Pricing, Legislation/Policy and Local resources
Libraries (JClouds, LibCloud, DeltaCloud, SimpleCloud, Apache Nuvem)	Open source projects	Multi-Cloud libraries	Directly managed	Singular Jobs, Periodical Jobs, Compute and Data Intensive Interactive application	Geo-location, Data location, Pricing, Legislation/Policy and Local resources

the provisioning flexibility of the direct approach. All discussed industry projects take either direct or trigger-action approach to application brokering.

Pricing awareness is the only brokering characteristic that can be facilitated by almost all Inter-Cloud projects - see Table II. Most federations do not support brokering considering any other of the predefined requirements. Few of them have limited awareness of data location, legislation/policy and local resources. On the contrary all directly managed Inter-Clouds cover the whole range of discussed requirements and thus provide means for adequate brokering of miscellaneous applications.

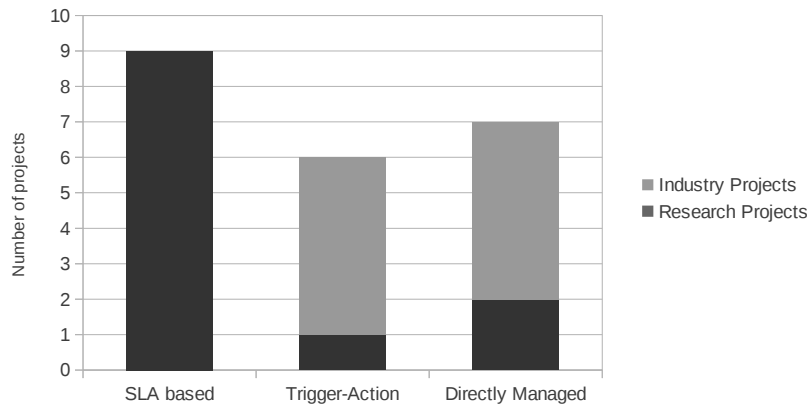


Figure 8. Inter-Cloud projects by Brokering Mechanisms

As a consequence most current federation projects are not tailored for *Interactive* applications, since they do not allow application brokering to consider such aspects. On the contrary *Independent* Inter-Cloud projects can facilitate all of these and thus are more general purpose in nature.

8. CONCLUSION AND FUTURE DIRECTIONS

In this work we have classified and analysed the state of the art in Inter-Cloud developments. More specifically we focus on how current Inter-Cloud projects facilitate the brokering of different applications across multiple clouds. This is a novel area of intensive research and development whose body of knowledge has not been well established yet.

We introduce classifications of Inter-Cloud architectures and brokering mechanisms. Then we classify Inter-Cloud applications and discuss their coarse-grained properties and brokering requirements. After an extensive analysis of the related literature we identify, discuss and fit into the aforementioned classifications 20 major projects. After that we analyse the state of the art and the trends in the area.

We have identified that there is a major difference in the directions that early research projects and industry projects are heading. While most research projects focus on developing Inter-Cloud federations, most industry projects provide services or libraries for direct provisioning and scheduling across clouds. Also most research projects focus on SLA based brokering, while industry driven ones focus on trigger-action based or directly managed brokering.

Both these two trends imply future work, which can be summarized as follows:

- **Advances in SLA specification techniques** - as discussed current SLA approaches are not suitable for specifying appropriate provisioning across clouds. Further work is needed to develop them.
- **Combination of brokering approaches** - it is unlikely that any of the discussed approaches will be sufficiently flexible to facilitate all kinds of applications. Thus it is worthy to investigate how they can be combined. For example some coarse-grained provisioning rules may be specified in an SLA, while fine-grained provisioning and scheduling policies can be implemented by trigger-action rules.
- **Application specific brokering** - further research is needed to define the best ways to broker specific types of applications across clouds. In this work the introduced taxonomy of distributed applications (see Section 5) was used as a starting point to identify the coarse-grained requirements for the major types of applications. Further work is needed to identify more specific requirements and brokering policies for specific application types - e.g. OLTP systems.

- **Improved Inter-Cloud environments** - as discussed many of the existing Inter-Cloud environments do not allow for adequate brokering of many types of applications. The improvement or development of new Inter-Cloud environments that allow for this is essential.

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