Towards Spatial Data Infrastructures in the Clouds

Bastian Schäffer[1], Bastian Baranski[1], Theodor Foerster[2]

[1] Institute for Geoinformatics, University of Münster, Germany
{schaeffer,baranski}@uni-muenster.de

[2] International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands
foerster@itc.nl

Abstract. Cloud Computing is one of the latest hypes in the mainstream IT world. In this context, Spatial Data Infrastructures (SDIs) have not been considered yet. This paper reviews this novel technology and identifies the paradigm behind it with regard to SDIs. Concepts of SDIs are analyzed in respect to common gaps which can be solved by Cloud Computing technologies. A real world use case will be presented, which benefits largely from Cloud Computing as a proof-of-concept demonstration. This use case shows that SDI components can be integrated into the cloud as value-added services. Thereby SDI components are shifted from a Software as a Service cloud layer to the Platform as a Service cloud layer, which can be regarded as a future direction for SDIs to enable geospatial cloud interoperability.

1 Introduction

Cloud Computing is one of the latest trends in the mainstream IT world (Gartner 2009a). A cloud metaphor is used to represent large networking and computational infrastructures. From a provider perspective, the key aspect of the cloud is the ability to dynamically scale and provide computational and storage capacities over the internet. From a client perspective, the key aspect of a cloud is the ability to access the cloud facilities on-demand in a cost efficient way without managing the underlying infrastructure and dealing with the related investments and maintenance costs.

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In this regard, Spatial Data Infrastructures (SDIs) undergo a transition from providing geodata towards providing web-based geoinformation (GI) (Kiehle 2007, Schaeffer et al. 2009). To provide this web-based geoinformation, massive processing tasks are required in a cost efficient way to maintain sustainability. In the past, the processing of geodata has been performed mostly on desktop machines and mainframes. Due to this requirement for massive processing capabilities, Cloud Computing is a promising approach. Additionally, this novel technology is beneficial to sufficiently scale these processing tasks on the organization's infrastructure or within an SDI. The problem of scaling can be demonstrated for the example in disaster management scenarios, which requires a large-scale computational infrastructure for extensive computations only for a short period of time. Another aspect related to scaling is the coupling of SDIs with the mass market domain such as the integration of volunteered geoinformation (i.e. collected via mobile phones) in SDIs. In this case many users create and share their geodata on-demand concurrently, which is seen as a beneficial application for SDIs to enrich existing databases in real-time. The risk management scenario as well as the volunteered geoinformation do not follow a fixed schedule (such as for instance the periodically update of data in an agency) and therefore require new approaches to technically meet the requirements and to limit the infrastructure costs. Therefore, Cloud Computing is a technical and economic opportunity for SDIs to support future geospatial applications. Moreover, it is also an approach for novel business to create, operate and utilize SDIs. All these aspects motivate to investigate the potentials of Cloud Computing for SDIs.

Thus, this paper presents a cloud-enabled SDI addressing some of the current obstacles of SDI development. Section 2 reviews the related concepts of Cloud Computing and SDIs. The cloud-enabled SDI is described in Section 3. The application of the risk management use case is presented in Section 4. In addition, Section 5 validates the scalability promise of the cloud computing paradigm with regard to the presented use case. Finally, Section 6 gives an outlook and concludes the findings.

2 Review of Relevant Concepts

This section provides a review of relevant concepts in the context of Cloud Computing and SDIs.

2.1 Cloud Computing

Cloud Computing is one of the latest trends in the mainstream IT world (Gartner 2008) (Gartner 2009a). Several IT companies such as Amazon, Google, Microsoft and Salesforce have already built up significant effort in this direction (see Section 2.3.1). The term Cloud Computing describes an approach in which the storage and computational facilities are no longer located on single computers, but distributed over remote resources facilities operated by third party providers (Foster 2008).

Cloud Computing overlaps with some concepts of Distributed Computing and Grid Computing (Hartig, 2008). Both, grid and cloud environments provide a network infrastructure for scaling applications by sufficient storage and computational capabilities. However, Grid Computing is applied by the scientific community for large-scale computations (e.g. a global climate change model or the aerodynamic design of engine components). Whereas Cloud Computing enables small and medium-sized companies to deploy their web-based applications in an instant scaleable fashion without the need to invest in large computational infrastructures for storing large amounts of data and/or performing complex processes (Myerson 2008). As a consequence, national and international grid infrastructures (for example the Worldwide LHC Computing Grid[1]) are typically funded by the government and operated by international joint research projects, whereas cloud infrastructures are operated by large-sized enterprises under economic aspects, such as Amazon or Google, enabling smaller companies to use their infrastructure (e.g. WeoGeo).

In essence, Cloud Computing is not a completely new concept, it moreover col-lects a family of well known and established methods and technologies under the umbrella of the term Cloud Computing. These well known methods and technologies are for example Software as a Service (SaaS) as a model for software deployment and virtualization as an efficient hosting platform (Sun Microsystems Inc. 2009). Besides, it describes a paradigm of outsourcing applications and specific tasks to a scalable infrastructure and therefore consequently enabling new business models with less up-front investments.

The following sub-sections describe the paradigm of Cloud Computing grouped by its characteristics and anatomy.

2.1.1 Characteristics

The key characteristics of Cloud Computing are the ability to scale and provide computational power and storage dynamically in a cost efficient and secure way over the web (ANSI 2009). Besides, a client application is able to use these resources without having to manage the underlying complexity of the technology. These characteristics lead to the following benefits:

- **Efficiency**
  From a provider perspective, Cloud Computing enables IT companies to

[1] http://lcg.web.cern.ch/LCG/

increase utilization rates of their existing hardware significantly. Existing infrastructures such as large data centers are now able to utilize their hardware infrastructures more efficiently by dynamically distribute their applications and processes to free available resources in an on-demand fashion. From a client perspective, the client's infrastructure can be utilized to the maximum and whenever more resources are needed, additional resources could be provided by the cloud.

- **Outtasking**
  By outtasking software and data to computational facilities operated by third parties, clients do not need to operate their own large-scale computational infrastructure anymore. Therefore, enterprises of any size - from Web 2.0 start-up companies to global enterprises - can decrease their costs for initial infrastructure and maintenance significantly. Thereby, fixed costs can be transformed into variable costs and create a business advantage. This allows companies to rather focus on their business model than to maintain and invest in the infrastructure (software licenses & hardware).

- **Scalability**
  Cloud Computing resources (i.e. storage or computational power) are allocated in real-time and cloud resources scale the deployed applications automatically on-demand (for example in case of high amounts of requests). This allows cloud users to handle peak loads very efficiently without managing their own infrastructures. For example, load-balancing or developing highly available solutions for their software do not need to be regarded by the cloud users because such solutions are incorporated in the cloud implicitly. By deploying applications and data in the cloud, clients are automatically able to scale up their computational capacities (for example from a few to hundreds of servers) in an instant and on-demand fashion.

- **On-demand**
  Allocating cloud resources on a real-time and on-demand basis helps enterprises to utilize large IT resources instantly and efficiently (see the aspect of efficiency). In contrast to classical long term outsourcing contracts, on-demand usage with pay-per-use revenue models enable cloud users to restructure existing business processes or even to realize the novel business models with little investment (Gartner 2009b). The total cost of ownership (including initial investment in hardware, software licenses, energy, fail-safety and technical engineers) of self-hosted data centers is in contrast to a Cloud Computing approach which minimizes start-up costs and helps enterprises to put new promising business models into the market.

An additional characteristic of Cloud Computing is the support of Service Level Agreements (SLA) defining different service quality guarantees (for example hotline support, web service mean up time or a specific numbers of accessible CPUs) and contractual penalty clauses. Such contracts are of general importance for cost-performance ratio transparency in SOA governance and therefore an essential characteristic for potential future geospatial business models with defined value propositions.

There are still a number of open issues for Cloud Computing. One open issue is the existing barriers of adopting Cloud Computing aspects in existing IT infrastructures, which is exemplified in the so-called "Open Cloud Manifesto"[2]. Especially the absence of cloud interoperability due to vendor specific cloud APIs can be seen as one major obstacle. These specific APIs bind the applications of the cloud users to specific cloud vendors and therefore complicate the migration of applications between different cloud vendors (i.e. vendor lock-in). Standards are needed and will be addressed by the Open Cloud Consortium.

Besides data backup and recovery responsibilities the outsourcing of confidential data from data owners to third party infrastructures is problematic in the context of security. Using public clouds as a deployment platform for applications and services is in most cases not suitable. Private cloud (clouds on private networks) maintained within an entity can help to solve this problem. The identified issues regarding outsourcing of data and reliability of infrastructures are not only specific to cloud infrastructures, but must be addressed for all kinds of distributed architectures.

2.1.2 Cloud Anatomy

The Cloud Computing paradigm replaces the classical multi-tier architecture model of web services and creates a new set of layers (Sun Microsystems Inc. 2009, ANSI 2009) as depicted in Figure 1. *Software as a Service* (SaaS) and *data Storage as a Service* (dSaaS) are the top layers and feature processing and storage facilities through web services. *Platform as a Service* (PaaS) is the middle layer and encapsulates complete development and runtime environments (for example operating systems, databases or web service application frameworks). *Infrastructure as a Service* (IaaS) is the bottom layer and delivers basic computational infrastructures as standardized services over the network. The bottom layer is then based on actual hardware provided to realize a cloud infrastructure.

[2] http://www.opencloudmanifesto.org/

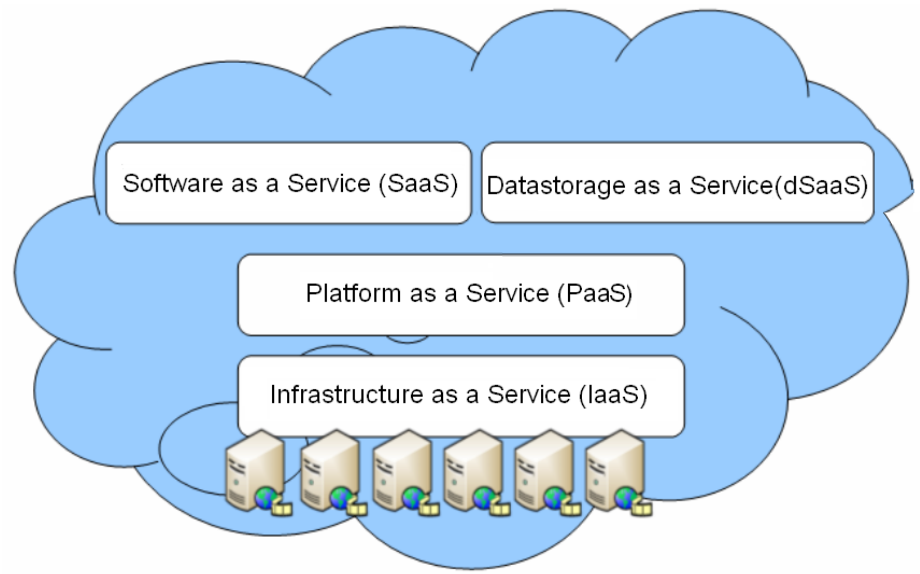

Fig. 1. A short overview about a typical set of Cloud Computing layers

2.2 Spatial Data Infrastructures

Spatial Data Infrastructures (SDIs) are technical, organizational and legal frameworks for geoinformation resources (McLaughlin and Groot 2000). SDIs can be designed differently. For instance, Bernard and Streit (Bernard & Streit 2002) especially focus on the service aspect of SDIs by specifying that an SDI enables the cooperatively use of distributed governmentally or privately held geodata and GI-Service across administrative and system borders. Whereas, McLaughlin and Groot (2000) emphasize the organizational aspect of "[…] delivering spatially resources, from the local level to the global level, in an interoperable way for a variety of uses."

The building blocks of an SDI are the geodata, its technical network, metadata, Web Services and standards (BKG 2002). Specific Web Services provide the geodata and corresponding metadata the Web. To realize communication sufficiently, the services have to be interoperable through standardized interfaces. Onstrud (Onstrud 2007) adds clearinghouses, partnerships, education and communication to this definition. Clearinghouses are used to uniformly search distributed geodata and actually obtain the geodata. Partnerships reduce redundancy and costs. Education and communication enables different entities to communicate knowledge and thereby learn from each other.

Several initiatives are currently in the process of establishing SDIs on multiple levels. From a top-down point of view, on a global level there is i.e. DigitalEarth and on the European level INSPIRE (European Council 2007). Many countries have started to establish their own national SDI, for instance the USA (USGS 2005), Canada (Geoconnection 2004), Germany (GDI-DE 2007), Portugal (Juliao 2009) and Denmark (Jarmbaek et al., 2009).

To actually build SDIs, standards and best practices are required. The Open Geospatial Consortium (OGC) is dedicated to standardize SDI services to enable interoperable communication.

Overall, the main advantages of an SDI for the participating organizations and society are (Bernard et al. 2005):

- Cost effective data production
- Avoidance of duplications
- Efficient data exchange and use over administrative and enterprise borders
- Improvement of decision making on the basis of available high value data.

Based on the presented concepts, Section 3.1 will describe current obstacles in developing SDIs, which can be addressed by integrating the cloud paradigm.

3 Cloud-enabled SDIs

This section provides the design of a cloud-enabled SDI by applying the concepts introduced in Section 2. At first, Section 3.1 analyses obstacles of SDIs. The findings of this analysis are additional input to design a cloud-enabled SDI (Section 3.2).

3.1 Obstacles in SDI Development

SDIs have shown a great potential for enabling the market value of geoinformation as for instance presented in (Micus 2004). However, current SDI development faces different challenges as for example volunteered geoinformation and data harmonization (Craglia 2009). On this basis, the following obstacles can be identified in SDI developments with regards to cloud computing:

- Upfront costs barriers
- Mass market requirements
- Legally binding performance allowances

SDI literature mentions also other obstacles such as organizational aspects (Ollen 2003) which are not considered here due to less relevance to the cloud context.

Volunteered geoinformation is beneficial for SDIs to enhance the availability of real-time data, but appropriate concepts to integrate such geoinformation are not yet available (Craglia 2009). In particular, volunteered geoinformation collected by ordinary users, who in some cases can provide up-to-date data, play an important role especially in risk management scenarios (e.g. geotagged pictures of flooding taken by mobile phones). These geospatial mass market applications, as the name implies, typically yield many concurrent requests which have to be processed. As Scholten et al. show (Scholten et al. 2006) scalability is a problem for SDI services. To meet these requirements of mass market applications for immediate response (i.e. below 5 seconds), scalable solutions are necessary.

Another challenge is the integration of real value-added information, provided by web-based processing. As already mentioned, SDIs are currently in a transition of the focus from data (provider-oriented) to information (user-oriented) (Kiehle 2006, Schaeffer et al. 2009). To generate this information, thorough processing facilities have to be integrated into SDIs. This integration requires large investments in computational and storage resources to handle the intrinsic complexity and huge volumes of geodata (e.g. LIDAR or real-time sensor data) as well as multiple and concurrent requests by mass market applications. Apart from the investments in large-scale computation infrastructure for processing, other investments related to SDI development such as software license costs are typically have to be considered. These investments can be seen as a major obstacle towards the full implementation of SDIs. For instance, to build up the Swedish SDI, more than 150M $ by an annual maintenance cost of 30M $ are reported by (Wigberg 2002). The Italian SDI has already cost over 400M €. Even though most of the money has been spent on data collection, it becomes clear that operating SDIs at a technical level is cost intensive. This shows also the investment of 80M € for infrastructure services for the Italian SDI over a 2 year period (Cappadozzi 2008).

Additionally, SDI initiatives with legal bindings such as INSPIRE (legally binding since 2007) explicitly require guaranteed response times for specific queries (INSPIRE, 2007) (INSPIRE, 2008). For example, the current requirement for processing is a throughput of 1 MB/second and a response time of the service below 1 second. Search queries need to be answered within 3 seconds and services must be able to handle up to 30 of these queries at the same time. Image downloads should have a maximum response time of 5 seconds. To meet the specified performance boundaries in peak times, scalable solutions have to be found which are not yet implemented in SDIs from a technical point of view.

3.2 Design of a Cloud-enabled SDI

This section presents a concept of a cloud-enabled SDI, which integrates the Cloud Computing paradigm with the SDI concept.

In general, there are two options for realizing the integration of Cloud Computing and SDIs:

- Option 1: Adopting Cloud Computing principles and standards to SDIs.
- Option 2: Migrating SDI services on top of a Cloud Computing infrastructure.

Following option 1, SDIs are limited to themselves by creating separate standards and markets and could not benefit from mainstream-IT developments in the future. The authors of this paper favour option 2 which is more beneficial for the GI-domain as it is more open to the mainstream IT world and thereby broadens the opportunities of the GI-domain. Therefore option 2 would in contrast to option 1 allow the combination of SDI and Cloud Computing benefits, while benefiting from new developments in the mainstream IT world at the sae time.

Mapping between SDI and Cloud Computing Components

From an architectural perspective, the integration of SDIs into Cloud Computing infrastructures is shown in Figure 2. In detail, data services (such as WFS) can be considered from a customer perspective as Software as a Service (SaaS), because they offer certain functionality, such as spatio-temporal query for datasets. From a data owner perspective, dSaaS is utilized, because the cloud can store the data served via standardized interfaces over a network. A typical case is a company for remote sensing, storing the large stream of data coming from their satellites and providing these images via data provision services to customers, without dealing with extending memory capacity in their IT infrastructure. SaaS as well as dSaaS rely on PaaS for e.g. the operating system, databases or web service containers, while IaaS describes the hardware level as shown in Section 2.1.2.

Processing instead of data storage aims at deriving information from data, can be seen as a typical SaaS application since customers can use the offered functionality, such as interpolating data on their side. The computation resources are provided via PaaS and IaaS. The same applies for portrayal services such as a WMS or discovery services e.g. Catalog Services (CSW).

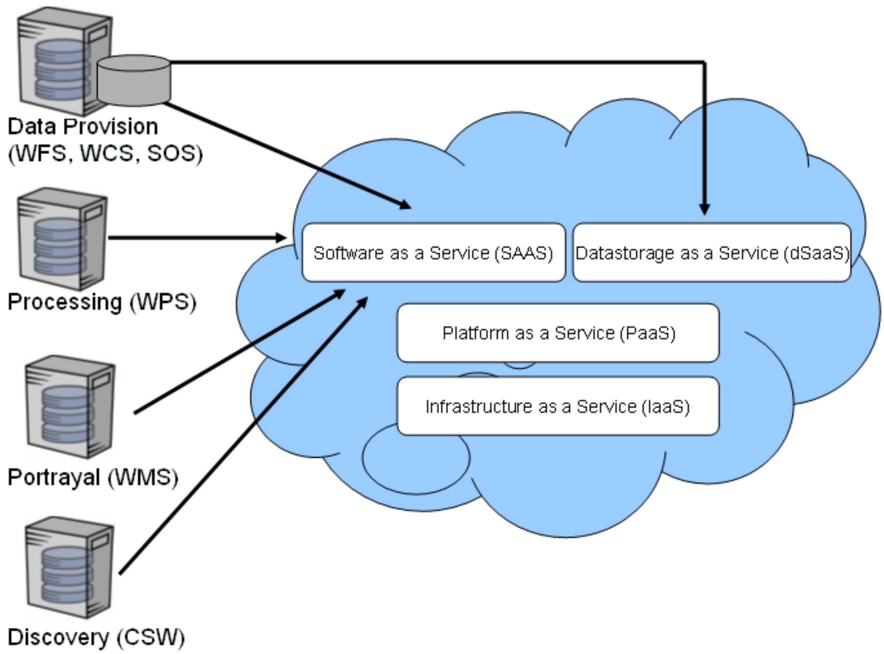

Fig. 2. SDI-Cloud Mapping.

The presented concept addresses the identified obstacles in SDI development (Section 3.1) as explained in detail in the following.

Upfront costs barriers

From a georesource (data/processes) provider perspective, the classic Publish-Find-Bind pattern of SOAs/SDIs (Figure 3) can be applied to the cloud-enabled SDI (Figure 4). According to this classic pattern the georesource providers host their services offering georesources on their own infrastructure and publish these services to a registry. This allows clients to find the georesources and bind (invoke) them. In other words, the georesources are accessed via services based on standardized interfaces over a network. This results in high upfront investments for the georesource owner to cover also peak loads or risk failing of the infrastructure.

Cloud Computing and in particular the aspect of outtasking can be utilized to overcome this high up-front investment for building and maintaining a large in-house IT infrastructure. By delegating computational and storage intensive tasks to third party providers in a cloud and using these tasks via services with standardized interfaces over a network, SDI services can be used in a cloud as shown in Figure 4.

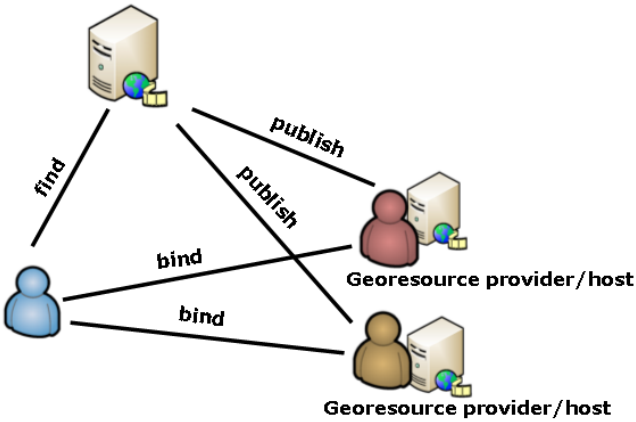

Fig. 3. Classic Publish-Find-Bind SDI pattern

The classic Publish-Find-Bind pattern still applies here, but the georesource provider uses the cloud to host their georesources. Therefore, there is a distinction in this concept between the roles of the georesource provider and georesources host. While the provider still publishes georesources which the customer can discover, the found georesources are bound from the cloud. Therefore, a business relationship has still to be established between the customer and the georesource provider. The revenue model for the georesource provider can be arranged in a flexible way. For instance, on-demand or flat-rate access models may be adequate as they are also the dominated revenue model in public cloud environments such as Google Apps Engine or Amazon Elastic Compute Cloud (Amazon EC2[3]).

Besides, by using standardized service interfaces, cloud infrastructures hosted by different providers can be used interchangeably from a cloud service consumer perspective. In other words, a client application does not need to be aware of whether a service is hosted in a cloud or not and which cloud provider is used. However, different cloud providers still have different internal requirements and capabilities which make it more complicated for the georesource provider to switch clouds for setting up a service in different clouds.

[3] For a complete cost schema, see http://aws.amazon.com/ec2

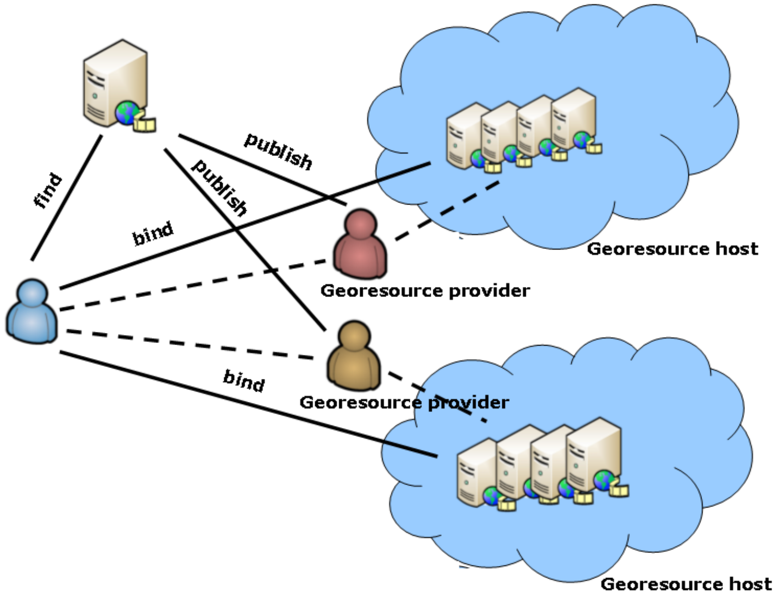

Fig. 4. Publish-Find-Bind in Cloud SDI

Mass market requirements

As identified in Section 3.1, current SDI concepts lack scalability, which is especially crucial for integrating mass-market applications into SDIs. SDIs can benefit from the ability of cloud infrastructures to handle large amount of requests, processes or data. By migrating services into the cloud, the georesources provided by these services are immediately available in a scalable fashion for on-demand use. Figure 5 shows, how the cloud expands from light blue over light violet to blue with the increasing number of user induced requests.

Conceptually, the scalability is automatically available through the cloud without touching the services itself. This implies that existing services can be deployed in a cloud environment without any adjustments to the service implementations.

When deploying SDI components on a cloud infrastructure, they can benefit from the cloud's scalability instantly, but still remain interoperable. Regarding the service interface, there is no difference between a cloud-enabled SDI service and a non-cloud enabled SDI service. In fact they can be used interchangeably and/or sequentially (in a composed workflow of traditional and cloud-enabled SDI components).

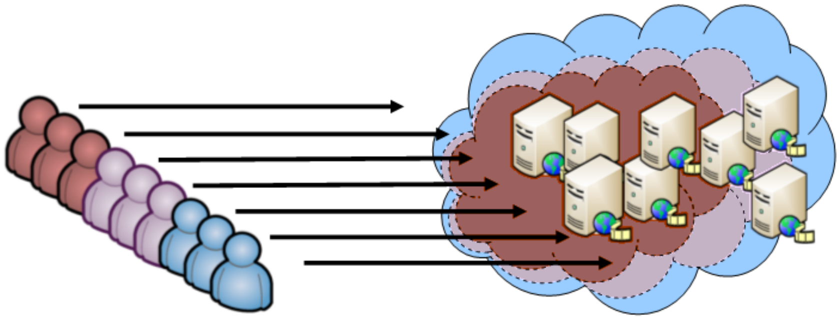

Fig. 5. Scaleable SDIs

Legally binding performance requirements

Existing SDIs which implement a legal framework such as INSPIRE have to meet specific Quality of Service (QoS) parameters as described in Section 3.1. This applies also for private companies providing SDI services which typically have to provide specific QoS levels. Especially the scalability aspect of clouds can help here to process even a large amount of requests in a given time frame. This aspect can be combined with the argument of up-front investments as described before. For instance, for start-up companies the legally binding performance requirements can be a limiting factor to realize innovative ideas if large infrastructure have to be acquired a priory to comply to the performance requirements. The Cloud Computing paradigm can be used to solve this obstacle, because it offers a low-cost way of delegating the performance requirements to a specialized third party georesource host (cloud provider).

For SDIs, this means, that the services of georesources have to be deployed in the cloud as shown in Figure 4.

These theoretic considerations concerning cloud-enabled SDIs will now be evaluated against the background of a real world use case with a special focus on the scalability of cloud-enabled SDI services over existing SDI services.

4 Application of the Use Case for a Cloud-enabled SDI

The scenario is settled in the context of a public risk management use case, in which in-situ-sensor data has to be analyzed for assessing a fictive fire threat in Tasmania. A similar scenario and involved services have been extensively presented in Foerster & Schaeffer (2007) for the area of north-west Spain. This section pushes the scenario idea one step further and leverages cloud enables services to create a highly scaleable solution in Tasmania.

The Amazon Web Services (AWS) together with an OGC Web Processing Service implementation hosting a buffer and intersection process is used in this scenario.

The Amazon Web Services product is a collection of services that are offering Infrastructure as a Service (IaaS), Datastorage as a Service (dSaaS) and some aspects of Platform as a Service (PaaS). The Amazon EC2 provides a web service interface to manage virtual machines (IaaS) that are used to host customer specific applications and can be scaled on-demand to handle peak load. The Amazon Simple Storage Service (Amazon S3) provides a web services interface that can be used to store and retrieve large amounts of data (dSaaS).

To deploy a WPS in Amazon EC2 and thereby to add the SaaS layer, an Amazon Machine Image (AMI) has to be configured. The AMI serves as a template for all instances that have to be setup by the Amazon cloud. Therefore, a WPS has to be installed on the virtual machine following the AMI template on top of a chosen machine setup (IaaS), operating system and servlet container (PaaS). In addition, the whole setup has to be configured to match certain scalability goals (expressed as rules). For this use case, the following rules were applied:

- 1 instance should be running at all times
- a maximum of 12 instances can be created
- if the CPU workload is below 20% in a 30 second interval, the number of instances should be decreased by 1
- if the CPU workload is above 50% in a 30 second interval, the number of instances should be increased by 1.

Once, the AMI is configured, deployed and started, the WPS is accessible via a single URL like any other non cloud-enabled WPS. For instance a standard web client such as OpenLayers or directly as a web service can be used to consume the service. In the given scenario, an expert would discover the URL (find) add the service to the OpenLayers client (bind) and buffer the given wild fire polygons. The resulting layer is then intersected by the given Tasmania road data.

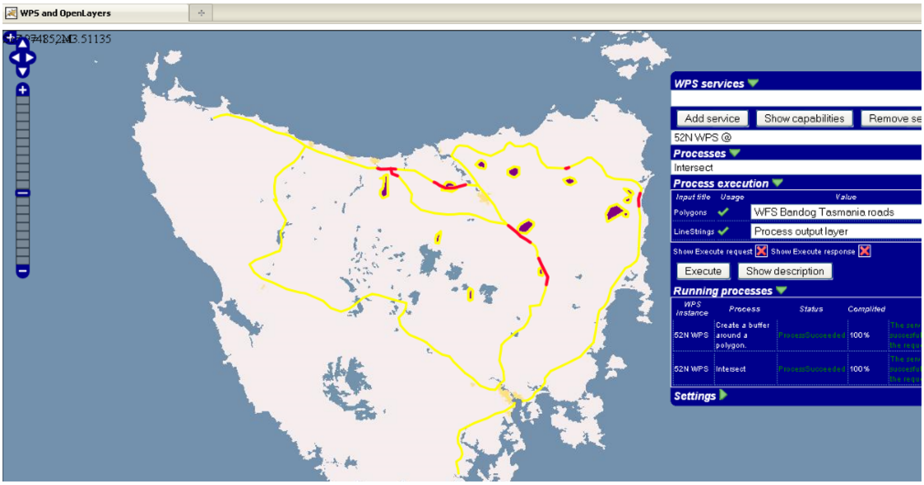

Fig. 6. Result (in red) of cloud enabled WPS intersecting buffered wild fires (violet) and road data (yellow) in Tasmania.

Overall, this allows the user to assess which parts of the road infrastructure are at risk by a fire (see Figure 6, read layer). With an increasing number of requests, the number of WPS instances in the cloud should increase as shown in Figure 5 to meet the scalability goals (i.e. constant response times) (see Section 5 for detailed results). In such risk management situations, in which multiple users with concurrent requests are expected and peak loads on the infrastructure are common, the information about the latest wild fires will still be processed and provided to the user based on real-time processing. The following section examines a stress test simulating such peak loads on the infrastructure and thereby demonstrates the scalability of cloud-enabled SDIs.

5 Stress Test

To demonstrate the scalability of cloud-enabed SDIs, we used a stress test to simulate an increasingly high demand of simultaneous requests (i.e. peak loads). A constant response time by the WPS deployed in the cloud was expected in contrast to a linear rising response time by a non cloud setting. The WPS was stress tested with the simple buffer algorithm, deployed in the Amazon Web Service framework as well as on a local and non cloud-enabled Tomcat installation. The geodata for that process was also delivered via a web service (deployed at the cloud(s) in the first case and deployed on the local and non cloud-enabled machine in the second case).

5.1 Methodology

A cumulative approach was used, starting with 1 and up to 200 requests that were sent nearly simultaneously in a short period of time to the deployed services. The elapsed time from sending the request to receiving the response on its own, as well as for the cumulative sum of the requests/response times was measured. In order to compare the local setting with the remote cloud settings, the results are normalized by only regarding the response time relatively to the maximum/minimum interval of all requests to the specific machine.

5.2 Results

Figure 7 shows the normalized response time of the online (Amazon Web Services) as well as of the local deployed WPS over the number of simultaneously sent requests. Normalization was reached by means of using the interval (min, max) as baseline. The response time of the remote WPS (monotonically increasing line) stays nearly constant up to 200 simultaneous requests whereas the local WPS response time (constant line) grows linearly. For the cloud approach, only one large peak at the beginning can be observed at the beginning and some smaller peaks during the rest of the execution.

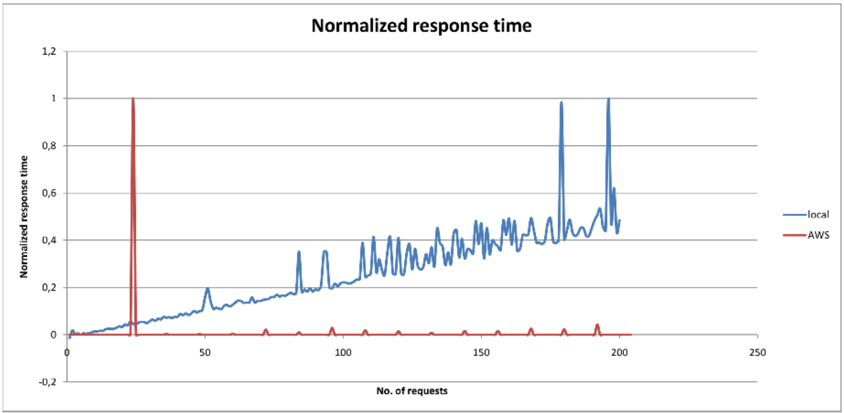

Fig. 7. WPS local vs. WPS in the cloud stress test results

5.3 Evaluation

The performance evaluation shows to some degree that a WPS deployed in the Amazon Web Service scales at high request rates as expected: The response time for many simultaneous requests stays nearly constant in contrast to the non-cloud deployment.

The peak in the beginning of the cloud curve (Figure 7) for the measured response times could be explained by means of managing the (virtual) server instances in the backend. Additionally, the number of instances is increased only by 1 in a 30 second interval, which means, that for the starting period not enough instances are available. We assume that the smaller peaks for the remote WPS are also related to minor background management tasks, such as setting up new instances.

6 Conclusion

This paper presents an approach for integrating SDIs and Cloud Computing technologies to set up a cloud-enabled SDI. A cloud-enabled SDI is identified as beneficial to address the major obstacles of SDI development (Section 2). Different roles in this cloud-enabled SDI are distinguished (Section 3). When integrating Cloud Computing and SDIs the existing publish-find-bind pattern for service interaction can be reused. Therefore, we see a paradigm shift from technological to economical aspects in contrast to a complete paradigm change, because the technical principles stay the same while economical aspects (upfront costs, maintenance, cost-effective production, etc, see section 1) motivate the technological shift.

It also became clear, that the way forward is to bring SDI components into cloud environments instead of adopting mainstream IT techniques such as Cloud Computing for SDIs. This will broaden the business opportunities for SDIs based on the high potential of cloud technologies. Therefore, we can foresee that the components, once deployed in an SDI, could be part of a cloud infrastructure service (belonging to PaaS) as there are already for instance databases or authentication APIs provided in a cloud, for georesources (geoprocessing/geodata).

As discussed, cloud interoperability from a client perspective is given for the geospatial domain because of the well established standards. From a provider perspective, the coupling with each cloud infrastructure is vendor-specific. Therefore, the advance of the SDIs regarding standardization can lead to easy cloud interoperability also for the provider in respect to georesources. Once the standardized SDI services are deployed in a cloud, they can be used by other cloud applications interchangeably. This implies that when a georesource dependent application is migrated from one cloud provider to another, the connection to underlying georesources providing services does not need to be changed due to its standardized access.

Another conclusion we can draw is, that Cloud Computing has the potential to create new business models for SDIs. These business models have to be distinguished from client and provider perspective. From a client perspective, the low up-front investment barrier by using cloud environments for SDI services allows companies to start new business models, which may have not been possible before due to high legally binding requirements. Besides, the outtasking of non-core task of a business process can lead to a modification of exiting business processes, which allows the overall business model to be more flexible to customer needs. This can lead on the provider perspective to specialized SaaS providers which can offer value-added services on-demand in a scalable fashion as for instance shown in the use case. These new SDI business opportunities have to be studied further in the future. Especially, the increasing distribution of smartphones seems to be a promising market, because applications on smartphones typically address the mass market but also lack large processing, storage and battery capacities, which makes it necessary to handle the data in a remote server environment such as the cloud.

The use case and further tests on the scalability part showed that cloud computing keeps its promises in terms of scalability. It could be clearly seen, that the response time stays constant in contrast to a linear increasing response time for a non-cloud approach.

As already discussed in Section 2.1, privacy can be a concern for sensitive data when they are given away to third party public cloud providers. The same problem applies to SDIs and the georesources provided via services in particular, because georesource could e.g. cover sensitive areas such as government buildings or are costly to create. However, certified cloud providers in analogy to certified tax accountants can be one applicable solution to overcome privacy concerns.

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