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Chapter 2: Architectural Principles for Adaptive Multi-Cloud Platforms

2.1. Introduction

Architectural principles and patterns that support adaptive multi-cloud platforms, able to make best use of the options available across different providers, are discussed. The particular focus is adaptation and elasticity, defined in the multi-cloud context, in addition to several other quality attributes. A modular architecture, built using well-established patterns, facilitates evaluation and the exploration of alternative options.

Multi-cloud solutions distribute workloads across multiple cloud providers, enabled by skewed pricing, specialisation, or distinctive features. Two broad strategies can be followed: vendor-agnostic, wrapping the capabilities of multiple providers in a single platform; and vendor-specific, addressing a particular cloud and orchestrating non-native resources on an ad hoc basis or using multiple clouds in a cloud-bursting manner. The separation of cross-cloud orchestration and internal management provide a clear responsi-bility boundary, while an orchestration layer based on recognised patterns simplifies the design of the policies that control scheduling decisions, deal with conflicts across cloud providers, and enforce compatibility with the underlying system SLAs.

2.1.1. Background and Significance

Multi-cloud platforms offer the potential to leverage the best services from multiple providers while avoiding the risks of vendor lock-in and single-point failures. These advantages are tempered, however, by challenges of interoperability and orchestration. Multi-clouds that are built to be vendor-agnostic require a high degree of standardization across clouds, while those that target best-of-breed, vendor-specific services demand careful planning of the orchestration strategy. Furthermore, maintaining consistency between multiple clouds adds yet another axis of complexity. When organizations make

decisions on deployment strategies, they must weigh the benefits against these disadvantages and select a strategy that aligns with their enterprise architecture.

For several organizations, particularly large enterprises and those in heavily regulated industries, concerns about compliance, security, reliability, or control of data ultimately lead to the choice of a multi-cloud strategy. Even their environments tend to evolve over time, forcing organizations to adapt their service deployments, scaling mechanisms, and cost-management approaches. A single-cloud service may become prohibitively expensive, another cloud provider may offer a more suitable service, or the load on individual services may shift in unpredictable ways. Designs that ignore the need for adaptivity risk delivering solutions that are inadequate or unnecessarily costly over their operational lifetimes.

Fig 2.1: Architectural Principles for Adaptive Multi-Cloud Platforms

2.1.2. Research design

The proposed analysis adopts a model-driven approach that blends architectural evaluation and design. The analysis builds on a foundational model and uses pattern-based techniques to extract architectural principles, platform architecture patterns, quality attributes, and a reference architecture suited for adaptive multi-cloud environments. The work defines the concepts, data sources, and evaluation criteria needed to support the analysis. Cross-cutting solutions, such as service discovery,

monitoring, and security management, are not addressed in depth to avoid unnecessary complexity.

Cross-cloud environments support application deployment on multiple clouds. These environments enable the distribution of components across clouds in response to business or technical requirements, thus increasing overall business value. Multi-cloud enables vendor lock-in avoidance, risk spreading, capacity boosts, quality improvements, and regulatory compliance. However, adapting application topology and deployment strategy dynamically across clouds causes considerable engineering effort.

2.2. Foundational Concepts

Adaptivity is a key requirement of modern cloud services. Enabling the automatic adjustment of resources in response to changes in demand—also called elasticity—reduces operational costs and increases efficiency. Dynamic provisioning adds to this by modifying the configuration of cloud components to improve performance when provisioning new resources returns diminishing returns. Adaptivity hinges on a collection of decision policies that perform actions driven factor, environment, or monitoring metrics. The detection of sudden, large shifts can be supported by tools like CUSUM control charts.

Multi-cloud is a well-known solution for avoiding lock-in with a single provider and improving redundancy. Abstraction layers placed between the application and the cloud have been shown to simplify the service and allow geographic distribution. Nevertheless, existing architectures fail to consider the adaptivity of both the application and the abstraction itself. Cross-cloud orchestration acts on the scheduling of requests to the providers, enforcing policies defined by a dedicated control engine and applying policies like load balancing, geo-replication, or service discovery based on the information provided by a telemetry layer that collects and processes data from the various components through a common data model.

2.2.1. Multi-Cloud Paradigm

The multi-cloud concept is the utilization of the services of heterogeneous cloud platforms, enabling organizations to assign workloads to the most appropriate service provider. Multi-cloud deployments can be classified into two main strategies: vendor-agnostic and vendor-specific. Vendor-agnostic architectures rely on a common control plane that can manage services from any cloud provider, avoiding vendor lock-in and supporting seamless service migration between providers. Vendor-specific solutions, by contrast, are either developed specifically for each target cloud platform or use a

platform-specific abstraction layer, benefiting from advanced features yet suffering from vendor lock-in.

The multi-cloud approach brings together the advantages of a cloud model while minimizing its drawbacks. It allows organizations to select the most suitable cloud provider for each particular operation, exploit resource price differences, and migrate workloads dynamically according to demand and pricing policies. Data centers can also be built using low-cost, low-maintenance equipment, as mission-critical operations can be directed to a cloud service provider. Dynamic resource scaling and cost optimization reduce the overall operational expenses of deployed services.

2.2.2. Adaptivity and Elasticity

A multi-cloud platform must support adaptivity. Adaptivity requires two complementary capabilities: elasticity, which allows the instantaneous change of the resource pool—i.e., scale in (release unused resources) or scale out (provision more resources), an operation commonly called autoscaling; and dynamic resource provisioning, autonomously provisioning and deploying new modules in an ad-hoc manner to accommodate changing requirements. These capabilities, which must work in concert with the appropriate decision policies, can be triggered by application requests or by crossing defined threshold values of dynamic run-time quality indicators such as latency or throughput.

With respect to elastic scale-out, quality indicators defined at the control plane for autoscaling decisions must be aligned (preferably, shared) with run-time quality indicators that determine the load distribution mechanism. Latency-based autoscaling must consider the resulting latency, while throughput-based autoscaling must take into account the target throughput level and the throughput distribution among replicas. With respect to dynamic provisioning, the quality metrics must support the identification of the need for a new module and the appropriate type of module to be provisioned. Dynamic provisioning, though in principle supported, is generally kept as a last-resort mechanism because of the complexity of automatically deploying an ad-hoc module for a multi-cloud application when a sudden peak occurs with little time available to discover and deploy an alternative solution.

2.3. Architectural Principles

Two types of architectural principles are relevant for adaptive multi-cloud platforms: foundational principles—those principles that any adaptation-enabled platform-based system development must be based upon—and quality attribute principles—those

principles that must be considered to support the quality attribute requirements of the system being developed. These principles, derived from seminal works in the area of cloud computing, form an adaptation-flavored architectural restatement, part of a more general cloud computing architectural style for platform-as-a-service in adaptive multi-cloud environments. The enlarged range of investigated adaptive cross-cloud platform architectures and the requirements posed as a consequence of providing adaptivity capabilities for such platforms have stimulated the articulation of a wider range of quality attribute principles and the definition of a reference architecture suited to the adaptive multi-cloud domain. With the aid of other available architectural artifacts—such as canonical technologies, architecture patterns, common—and reusable—components and services—conformance evaluation becomes feasible.

A platform-based system-development approach supports the articulation of architectural principles and the identification of a suitable adaptation-enabled reference architecture. Modularization of an adaptive multi-cloud cross-cloud platform system into architecturally significant components is feasible. These components are an orchestrator service, a decision-making policy-enforcement service, an abstraction-layer service, a data-telemetry service, and a system security service, all of them enabling interaction either directly or indirectly. The services are able to communicate through an event-driven mechanism, facilitating loose coupling and high resilience to the exchange of any redundancy-requiring telemetry data. Quality attribute-properties such as performance and scalability, reliability and availability, security and safety, and evolvability and maintenance that underlie the developed architecture are suitable to be assessed based on these five core components.

Fig 2.2: Architectural Principles

2.3.1. Modularity and Abstraction

The architecture of a cloud platform is composed of a set of modules that work together to meet the needs of its users. The boundaries and interfaces of the components should be defined according to the goals of a specific implementation. The modules that are part of the system should be abstracted from the details of their implementation in order to allow the use of heterogonous technology stacks and algorithms. The internal details of a module should be encapsulated, hiding information that other modules do not need. When the objectives are met, the implementation of a specific module can be changed without affecting other modules.

The codebase can be layered to separate different concerns (e.g., cloud orchestration and application development) or different technology stacks (e.g., orchestration and data management). The layer interface defines the contract that a layer must fulfill to the layers above it. The separation of layers allows different technology stacks for different functions in a platform, enabling the use of the most appropriate option for a specific purpose. For instance, the Telemetry module implemented using a particular technology at a particular moment may not be the best on the long term; however, it can be replaced without affecting other parts of the platform if the layer interface is properly defined.

2.3.2. Interoperability and Standards

Adopting and composing services offered by different cloud providers should not lock organizations into specific vendor environments. Such vendor lock-in may be avoided or mitigated when existing and future applications deployed in multi-cloud environments adopt open standards for inter-cloud communication. For such standards to be effective, they should govern the definition and implementation of all essential features of a given service, including communications protocols, API definitions, data formats, QoS and security measures, and SLA guarantees. The use of open standards ensures that applications composed of services from different clouds communicate effectively, thus enabling the implementation of cross-cloud orchestration mechanisms.

Adopting open standards for service inter-operation undoubtedly increases the complexity of implementing cloud services since different clouds are required to comply with those standards. As a rule, an increased complexity of service implementation is accompanied by a degradation in performance. However, in a multi-cloud environment, such complexity and performance degradation may be compensated for by the greater flexibility and cost effectiveness provided by the possibility of selecting services from different cloud providers.

2.4. Platform Architecture Patterns

Distinct architectural patterns for platform cores and control planes are essential to efficiently exploit multiple cloud infrastructures and services. Suitable abstraction layers for data plane operations, together with a well-designed cross-cloud orchestration approach, are equally important. Cloud-edge orchestration is responsible for deploying, managing, and monitoring applications using the currently available cloud data planes, while cross-cloud orchestration utilises cloud infrastructures and services according to the users APP system and non-functional requirements defined in the service-level agreements.

An efficient scheduling policy for must-run applications takes advantage of the performance characteristics of different cloud suppliers at any given time, preventing performance penalties and contrast limitation policies. Security conflicts that may arise when moving data and application resources across different clouds are addressed through the adoption of a policy engine, which applies data control and auditing policies and implements integrity and confidentiality of the managed data. The resource-usage profiles of multi-cloud applications enrich and complement the knowledge of the policy engine to improve security and operational efficiency. These patterns enhance the design of multi-cloud platforms, enabling the development of flexible, easily modified systems adapted to modern business practices.

2.4.1. Abstraction Layers and Control Plane

An adaptive multi-cloud platform associates multiple cloud services by orchestrating resources in both public and private environments according to real-time conditions and requirements. The design satisfies the architectural principles presented earlier, recognizing modularity and abstraction as fundamental guidelines. The platform embodies three abstraction layers, each encapsulating specific essential functions. The control plane coordinates the multi-cloud architecture and allocation, while the data plane aggregates the service-providing elements.

Abstraction layers serve to delineate areas of functionality, each providing a distinct set of services to its users, who might be external services, layers higher up the stack, or both. An abstraction layer must encapsulate its functionality in such a way that external actors need not be concerned about implementation details of any of the functions. The interaction of actors in the architecture is established via interfaces defined at the boundaries of the abstraction layers. Elements implementing the functions at the leading edge of the layers may expose interfaces responsible for different aspects of interaction, while interfaces directed at core components shall be grouped as abstraction layers.

These patterns of interaction can be viewed either as layers or as separate modules, according to the zooming level, and correspond to the different views of the architecture.

2.4.2. Cross-Cloud Orchestration

Inter-cloud orchestration governs apps running on multiple IaaS clouds and is responsible for operation lifecycle management of those apps. Component-based implementation addresses multi-cloud service adaptation and enables horizontal scaling. Multi-cloud-enabled services can be installed and operated using the interfaces exposed by different providers. Business-logic-aware resource provisioning supports scaling each component by taking characteristics and dependencies of each component into account. Policies and rules permit automatic scaling of business services according to application-defined conditions.

Cross-cloud service orchestration manages the operation of distributed services across IaaS providers spanning multiple administrative domains. Cloud providers maintain the created services and have freedom in choosing where to place physical resources. Such a placement of resources can be utilized to process cloud-specific policies. The cross-cloud service provisioning framework manages the life-cycle of cross-cloud services. Deploying or provisioning a new service is a multi-phase process. The service provisioning request is received by the cross-cloud orchestrator which then finds suitable resources across multiple clouds. The of actors is either a requesting or an executing role. The orchestration engine receives the service provisioning request from the client based on a predefined business logic. The request flow with respect to the actors is shown and Messaging servers are the key components of a chat process that can be operated via public cloud.

Cross-cloud scheduling orchestrates applications to be processed in multiple clouds by incorporating business rules and resource availability. Cross-cloud service deployment employs component-based implementation to adapt to different cloud environments. Conflict resolution mechanisms and policies formalize the operation of business threads across multiple clouds during the operation cycles. Execution control ensures reliable service execution across clouds and derives execution direction taking into consideration the coordination and collaboration requirements of various application components.

2.5. Quality Attributes and Evaluation

Quality Attributes and Evaluation

To evaluate the attainment of specified adaptivity requirements, supporting quality attributes must be defined. Performance and scalability are critical for any platform,

addressing throughput and latency targets under load, the ability to scale operations horizontally by incorporating more cloud resources of the same type, and/or vertical scaling through load distribution to additional operational instances. With likely design and implementation heterogeneity, scaling options per cloud are usually distinct—some across geo-locations and some limited to specific regions—while usage patterns for LVM should help identify the right clouds at the right times. Moreover, adaptivity should facilitate vertical scaling regardless of planning and implementation.

Reliability and availability are also paramount. Recovery Time Objective (RTO) and Recovery Point Objective (RPO) targets, along with redundancy and fault-tolerance requirements, drive data replication for fast state recovery. Replicated data, stored in multiple regions and/or clouds within a region, further improves availability and tolerates the failure of an entire cloud or region. For multi-cloud platforms, fault tolerance goes beyond the individual service level to cover the entire platform. Detection and mitigation of orchestration service unavailability—possibly combined with policy-engine service detection—and the absence of nefarious operations (e.g., across clouds without scheduling awareness) should therefore be addressed. In practical deployments, especially for certification, redundancy and orchestration ought to be subject to specific attention, whereas other quality attributes are usually more pertinent for the architect and designer.

Fig 2.3: Quality Attributes and Evaluation

2.5.1. Performance and Scalability

Performance and scalability require careful design to meet Service Level Agreement (SLA) targets. Throughput and latency objectives shape overall system architecture, service deployment and configuration decisions, and provisioning models during operation. SLAs with service users specify throughput and latency targets, taken into account when selecting a multi-cloud serving topology.

Horizontal scaling strategies consider throughput, availability, and cost. Load distribution models define how user requests are routed to back-end services on different cloud platforms. An autoscaling mechanism manages horizontal scaling by adding or removing VM instances according to load. Vertical scaling is another option for boosting throughput during peak demand; cloud platforms offering VMs with different configurations can be switched or reconfigured dynamically.

2.5.2. Reliability and Availability

Reliability and availability are vital quality attributes for multi-cloud platforms supporting mission-critical applications. Reliability specifies the ability of a system to avoid service failures anticipated during specified periods, while availability indicates the fraction of these periods during which the system operates correctly. For disaster recovery purposes, the two indicators are often expressed in complementary terms: recovery time objective (RTO) and recovery point objective (RPO). The RTO indicates the duration of a service outage or suspension tolerable for a particular application, while the RPO specifies the maximum acceptable level of data loss incurred when recovery becomes necessary. Both indicators should be expressed in business terms rather than purely technical measures, such as time— for instance, in missed invoice payments. To meet reliability and availability requirements, platforms may exploit service redundancy across physically separated cloud providers. Higher availability can also be achieved by combining cloud resources with other existing resources, often federated with clouds, such as on-premise systems, system integrators, and managed service providers.

Fault-tolerant patterns based on redundancy may be implemented to handle most types of failures, but all such patterns rely on providers being able to re-instantiate cloud resources automatically in a working state, which is not always satisfied. Properly specifying a fault model for an application is critical for a recovery policy to be practically viable. A more general failure model is to consider broken parts of the application rather than individual resources, and allow replication only for those parts subject to such failures. Recovery is often automated, but excessive automation should be avoided: once an emergency is over, human intervention is often necessary to put the system back in normal operating conditions.

2.6. Reference Architecture for Adaptive Multi-Cloud

A reference architecture for adaptive multi-cloud platforms delineates core components and interaction patterns. The core modules include a cross-cloud orchestrator, decision-making policy engine, control abstraction layer, non-functional telemetry monitors, and a security implementation module. The collaboration between these components is specified through message flows, an event-driven interactions interaction model, and the contribution of each component to the execution of cross-cloud processes.

The proposed reference architecture represents a foundational model that can guide the design of specific adaptive multi-cloud platforms. The specification of the modules helps cloud architects identify or develop suitable implementations, while the delineated interaction patterns provide instructions for correctly interconnecting the modules. Further refinements are essential to support specific deployment scenarios and achieve the adaptability requirements of concrete platforms. Moreover, the combination of modules may evolve to enable new functionalities or simplify cross-cloud processes. For instance, incorporating additional modules can facilitate the control of cloud costs. Missing modules may also be integrated to provide implementations for non-functional attributes ignored in the base architecture, or to fill gaps inherent in the selected implementations, thereby ensuring quality attribute targets.

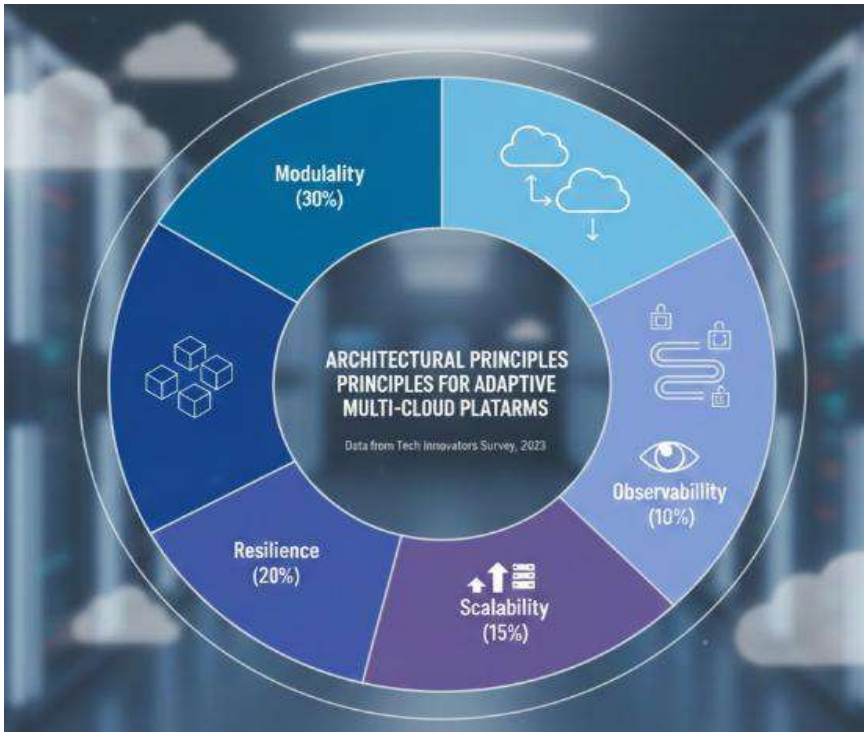

Fig 2.4: Architectural Principles for Adaptive Multi-Cloud Platforms

2.6.1. Core Components

The architecture comprises the following core components:

1. **Multi-Cloud Orchestrator**: It manages the cross-cloud orchestration, enforcing policies throughout the data and control planes. The orchestrator periodically monitors and analyzes the system behavior by accessing abstracted telemetry data and actively controlling other modules, such as enforcing tenant policies through the policy engine and managing security requirements.

2. **Policy Engine**: This module defines the adaptive behavior of the platform by enabling application-specific vertical and horizontal scaling specifications, user-defined control policies (enabling load balancing, disaster recovery, backup policies), and service-level agreement definitions for cross-cloud orchestration policies.

3. **Abstraction Layer**: This layer is essential for cross-cloud deployment and orchestration. It abstracts away cloud-specific details and provides a unified, simplified, and well-defined service and virtualization model for all application modules. Cloud services are accessed through the abstraction layer, either via Service Level Agreements or directly through the orchestration module.

4. **Telemetry Module**: This module collects performance- and reliability-related log data from cross-cloud applications and infrastructure and exposes this data in an abstract manner. Internal modules consume telemetry data to analyze and react to application behavior. Telemetry data generation and collection mechanisms can be implemented in a cloud-agnostic manner or can be explicitly included in Service Level Agreements of applications deployed on multi-cloud platforms.

5. **Security Module**: Based on defined cloud provider security policies and application-specific security policies, this module guards the data by utilizing cross-cloud data encryption/decryption mechanisms and ensures a secure communication pathway across clouds. When active, it receives real-time alerts and disables/reenables data encryption based on monitored events. A rule-based access control for cloud infrastructure can also be implemented.

2.6.2. Interaction Patterns

The interaction patterns among the core components of the reference architecture for adaptive multi-cloud platforms are depicted in Figure 3. The orchestrator module is at the heart of the architecture. It receives telemetry data, both from the monitoring system and the policies, which indicate whether actions are necessary, and later communicates commands or requests to the components of the abstraction layer. The abstraction layer is responsible for hiding the details of the individual cloud providers and exposing a

unified interface to the rest of the system, being only accessed by the orchestrator. This layer contains a security module that manages credentials and token generation for authentication and access control. When an operation requires a cloud resource to be created, the orchestrator consults the telemetry component about the availability of resources and, if necessary, the policy engine to evaluate the feasibility of the operation. This last component is also responsible for triggering the creation of cloud resources when required.

In addition to the interactions involving the orchestrator, the telemetry module reacts to events coming from the monitoring system that signal the need for action.

2.7. Conclusion

A declarative statement of principles, pragmatic patterns, and a reference architecture form the contributions. Openness to cloud providers is an orientation for architectures and solutions, not a prescription against selecting vendors or an encouragement of mediocre results from massive international collaborations. The separation of a system's control and data planes favours such selection and hosting choices: nonsecret, highly scalable digital applications can run with lower costs and better performance when they are hosted in the nearest region of the cloud provider in high-availability mode. The combination of orchestration across cloud providers, resolution and provision of resource-usage conflicts, and enforcement of policies across domains is a holistic approach to developing multi-cloud systems with deployable architectures in the different multi-cloud contexts.

Enhancing the existing reference architecture for cloud mitigation strategies to monitor the quality of data ingested from and delivered by the cloud provider seems an attractive path. The exploration of a layered architecture for orchestrating a multi-cloud system based on an event-driven information flow design is an appealing initial direction for research on the deployment of a multi-cloud system on a specific cloud provider.

2.7.1. Future Directions

The need for adaptation has been highlighted, along with a consolidation or reiteration of adaptivity requirements and a discussion of how they can be achieved through autoscaling, dynamic provisioning, key decision policies, and the critical metrics that drive them. A conceptual architectural foundation for adaptive multi-cloud platforms has been established that reflects these requirements and has the potential to address the limitations hindering the effective and efficient use of multi-cloud infrastructures. The combined analysis of a set of core principles, two fundamental architecture patterns—

abstraction layers and control plane, and cross-cloud orchestration—and a reference architecture for adaptive multi-cloud platforms represent a pragmatic contribution of immediate relevance. Essential quality attributes have also been identified, enabling straightforward evaluation by platform designers and builders.

Yet the architectural exploration remains partial. Although key quality requirements have been detailed, others—including performance and scalability, reliability and availability—are only briefly considered here. A richer exploration of these attributes, not only in isolation but also considering interdependencies and trade-offs during quality evaluation, is clearly called for. Moreover, the modular approach to quality-attribute evaluation can be extended to inform individual components in greater detail. Beyond quality attributes, further research can refine specific principles, patterns, and modules; surface additional patterns; provide implementation guidance; and explore how existing cloud-native applications can be migrated to an adaptive multi-cloud architecture without introducing significant development overhead. .

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