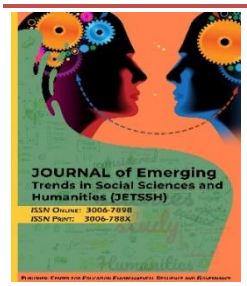

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Evaluating the Architectural Trade-offs of Micro Services Versus Monolithic Designs: An Empirical Analysis of Scalability and Maintainability in Enterprise Environments

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ABSTRACT

One key problem in enterprise software is the different software architecture problems. The two popular architectures are monolithic and microservices architecture. A review of the literature indicates, however, that current research tends to focus on the assessment of These quality attributes have been studied individually, with limited evidence to support their joint constraints. To overcome this gap, the present study has adopted a systematic secondary data analysis based on a comparative study. Evaluation and Evidence Extraction Synthesis (CEES) framework, a synthesis of empirical findings. From recently published peer-reviewed studies comparing both architectural styles. The analysis combines quantitative Integrate performance evidence and qualitative maintainability properties in one architecture evaluation. Both architectures showed similar performance under baseline workloads but not under overloads; Larger datasets led to increases in response time as the monolithic architecture broke down to a 20 s response time for 10, and then 50, concurrent users. The microservices architecture, on the other hand, maintained a better performance of a 15 s response time. What the results also reveal is that although the microservices promise numerous benefits in the areas of scalability, modularity and fault isolation, these benefits are substantial, but come with the added complexity of managing distributed communication, orchestration, and infrastructure. The study finally demonstrates that the choice of architectural style should be based on the needs of the organization, not technology.

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1. Introduction

Software architecture is the essence of contemporary software systems, providing the structure and relationships of software components and how they are deployed. Decisions made during the design stage have emerged as significant factors in the quality of software, both today and in the future, as enterprise applications continue to mature in the face of digital transformation, cloud computing and the growing dynamism of business needs. In today's organizations, software systems must be both high performing and able to evolve quickly, deploy frequently, handle failure gracefully and be efficiently maintained. Choosing an appropriate architectural style is, therefore, one of the most significant strategic decisions in enterprise software engineering which affects enterprise software systems' scalability, maintainability, reliability, and life cycle cost.

Monolithic and microservices architectures are two opposite approaches to enterprise application development in the present day's architecture paradigms. Monolithic architecture provides a presentation, business logic, and data access layers all in one deployable unit that is executed in a centralized environment. In general, this architectural style has been popular due to its ease of development, deployment, and operational management, including the ease by which it can be deployed at an enterprise level. This architectural style is popular because it is easy to develop, deploy, and operate, especially when the application's functional requirements are clearly defined and the business requirements are relatively stable. As enterprise systems grow in size and scope, however, tightly coupled components can get harder to modify, test, and scale, and can lead to increased maintenance requirements, slower deployments, and an increasing debt of technology.

To tackle these shortcomings, microservices architecture has become an architectural paradigm that is being widely used in cloud native computing. As opposed to the monolithic, microservices divide applications into namesake services that are loosely-coupled and collectively deployed as modules within specific business functions. It enables independent development, scaling to multiple levels of services, support for diversity of technologies, and isolation of failures and supports DevOps practices and continuous integration and continuous deployment (CI/CD) pipelines. Many large technology firms have found that microservices can help with highly scalable, continuously evolving enterprise systems and have proven their value. Many large technology companies have shown how useful microservices can be to their enterprise systems where they need to be highly scalable and continuously evolving, including Netflix, Amazon, Uber, and Spotify. However, these benefits come with increased complexity of distributed systems, additional overhead, service orchestration issues, data consistency problems, security management challenges and complex monitoring needs. This means that microservices offer some benefits in terms of quality attributes but also pose novel engineering challenges that need to be addressed.

As enterprises increasingly move to cloud-native, the question of whether monolithic or microservices architectures should be used has grown more heated. The studies in recent years have come to the conclusion that it is not a universally best architecture, but the architectural choices should be made based on the organization's goals, application features, maturity of development, and requirements for software quality. Recent studies have shown that both the styles of architecture come with their own set of compromises. Monolithic and microservices both excel in certain areas: microservices excel at modularity, deployment flexibility and horizontal scalability while monolithic systems excel at the issues of deployment complexity and single governance. They come with some complexity of infrastructure, high-valued properties and skills to properly manage distributed software ecosystems, and/or higher operating expenses, but these are sometimes balanced by advantages. As a result, the selection of architecture has become a multi-dimensional problem due to technical, organizational and economic factors.

Among the main Software Quality Attributes impacted by the architectural design in Enterprise Software Systems, is scalability and maintainability. When deciding between systems, for highly dynamic organizations with cloud-

based businesses, scalability is a factor that plays a big role in the way that a system can accommodate additional workloads without any downturn. Concurrently, maintainability is the ease of changing the software, testing it, adding features to it and having it evolve throughout its operational lifetime. These factors have a profound impact on software development expenses, deployment rate, technical debt and overall business agility. As a result, enterprise organizations are looking for architectural solutions that can meet the requirement of balancing scalability and maintainability instead of optimizing just one quality attribute.

Although there is a huge volume of research on the differences between monolithic and microservices architectures, there are some shortcomings in the existing literature. In the past, studies have paid attention to single architectural quality attributes and not explored their collective impact on enterprise software systems. Studies regarding scalability mechanisms have been conducted in recent years and focused mainly on the mechanisms and techniques for auto scaling, workload prediction, and resource optimization, while paying comparatively little attention to the implications of long-term maintainability. Likewise, empirical migration studies have tended to concentrate on performance measures like response time, throughput and error percentages, and offered little assessment of maintainability measures like coupling, modularity, technical debt and software evolution. Additionally, most comparative studies are conceptual or literature-based studies that offer limited empirical data on the relationship between scalability and maintainability for realistic enterprise situations.

This restriction is a major problem for software architects and enterprise decision makers. No single quality attribute drives architectural decisions; there are many interdependent, compounding quality attributes that collectively shape software quality and sustainability. Organizations may make decisions about architectural approaches on a basis that is largely based on isolated performance gains, industry fashion or organizational preference, without a comprehensive empirical investigation into whether the approaches are scalable or maintainable, or whether they meet the other architectural trade-offs that are important. Furthermore, with the development of new architectural solutions like modular monoliths, the architecture argument is becoming a gray area, and the binary monolithic versus microservices isn't an adequate evaluation structure and should be more evenhanded and based on the evidence.

Hence, the goal of this research is to assess empirically the architectural trade-offs between monolithic and microservices designs, while both scalability and maintainability are considered in enterprise environments. This study brings together these two views to examine them as two parts of a single investigation, as opposed to the other studies that tend to study them separately. This research aims to offer empirical evidence of the performance of each architectural style on the important dimensions of quality, and to find the situation(s) in which one architectural style is more suitable than the other. The results of this study will help software architects, software development teams, and organizational decision makers identify a software architecture that will maximize operational performance while minimizing software evolution costs. In addition, this study builds upon the existing body of knowledge as it fills the identified research gap regarding integrated assessment of scalability and maintainability, and extends the knowledge of evidence-based architectural decision-making for modern enterprise software systems.

2. Literature Review

2.1 Software Architecture

In this section, the theoretical basis for the study is laid and the importance of software architecture in enterprise software engineering is explained. Software architecture is the overall structure of a software system that includes its elements, their relationships, their interfaces, and the principles used to design and develop it. It acts as a blueprint to direct software development processes throughout the systems life cycle and directly affects quality characteristics of the software like scalability, maintainability, reliability, security, availability and performance.[1] The digital transformation, cloud computing, distributed applications and the ever-increasing pace of software delivery have made modern enterprise systems more complex. Therefore, the use of appropriate architectural style has become one of the most crucial decisions as a part of software

development. Architectural styles will influence the ease with which software can be scaled as load grows, integrated with new technologies, respond to changing business needs, and enable continuous deployment (CD) processes.[2]

Software architecture goes beyond the technical aspect of software development; it has an impact on the productivity of the organization, the cost of software development, risk management and sustainability of the software system. Technical debt is a common negative consequence of weak architecture that results in high maintenance expenses, deployment issues, and poor scalability. On the other hand, robust architectures offer more flexibility, modularity, and durability, which allows the business to adapt to the dynamic business landscape efficiently. The software architectures are broadly categorized into different architectural styles like layered architecture, service-oriented architecture (SOA), event-driven architecture, monolithic architecture and microservices architecture. In this group, two are receiving a lot of interest as they embody two opposing paradigms in enterprise software architecture design, namely monolithic and microservices. In contrast to monolithic architectures, which focus on simplicity and centralized development, microservices advocate for modularity and independent deployment, along with distributed system design. New research shows that neither architectural style is inherently better; rather, it must be based on the complexity of an application, the maturity of an organization, the operational capabilities, and expected scalability needs. [3] Thus, knowledge of software architecture gives the theory foundation to the evaluation of the pros and cons of monolithic and microservices architectures in terms of their scalability and maintainability. This knowledge is then built on as the rest of this literature review is elaborated.

2.2 Monolithic Architecture

Monolithic architecture is one of the oldest and most widely-used architectural paradigms in software engineering. In this method, the whole application is built, released and kept as a single executable file. All the functional components such as user interface, business logic, data access layer, and database interactions are tightly coupled and integrated within a single codebase. Since all the modules are running in the same runtime environment it is possible to communicate between each other by direct function calls, without any network based messaging. From the past monolithic architecture has been preferred because of the simplicity of their development, deployment and infrastructure needs. Monolithic systems are also commonly used by SMBs because they do not need extensive operational resources and a consistent technology and framework can be used to manage the development of an application. Centralized code management also facilitates the debugging, testing and system monitoring of the software during the initial stages of development.[4]

While these benefits are apparent, the drawbacks of monolithic become more apparent as the size and complexity of enterprise applications grow. All application components are tightly coupled, meaning that changes to one part of the code can have an adverse effect on other parts that function in unrelated ways, thus adding to the likelihood of regression defects. In the same way, it becomes more difficult to deploy due to the fact that updates to even smaller components result in a rebuild and redeployment of the entire application. These attributes decrease the speed of software development and increase the duration of software releases.[5]Another significant drawback of monolithic systems is their lack of scalability. Scaling needs to be done at the application level, not at the individual component level, since the application is a single deployment. This results in poor allocation of computational resources in cloud environments which can lead to high operational costs. Moreover, as the size of the codebase increases, they get harder and harder to read and maintain, leading to higher technical debt and poor maintainability[6].

However, new industrial reports illustrate that monolithic architecture is still very successful for applications with relatively stable business requirements, startups, and small-to-medium business applications. Moreover, the advent of the modular monolith concept shows that many organizations are still using monolithic architectures, but are implementing better modular design principles to increase their maintainability and decrease their coupling. The monolithic approach is not to be considered dead, but an architectural solution that is appropriate to

particular organizational and technical needs.[3]

2.3 Microservices Architecture

One of the most impactful software architectural paradigms today has become microservices in cloud-native computing and enterprise application development. While monolithic architecture packs all of an application into a single deployment unit, microservices break up business functionality into many smaller, independent services that communicate via lightweight API protocols like RESTful, gRPC, or asynchronous messaging. They have independent business logic, data storage, deployment lifecycle, and can be developed and operated independently by each service.[7] Micro-services are an integral part of the growing popularity of cloud computing, containerization (e.g., Docker), orchestration (e.g., Kubernetes), and DevOps (e.g., DevOps practices). These technologies enable organizations to deploy, monitor, update and scale individual services without impacting the entire system. Therefore, microservices greatly enhance the agility of the organizations as multiple teams can create different services simultaneously and concurrently.[8] It is one of the key benefits of microservices that they are horizontally scalable. Each service is independent from the others, meaning that only services that are heavily used need to use extra computational resources, which in turn helps to improve the use of resources, and therefore lower the infrastructure costs. Fault isolation also makes the system more resilient since failures in a service do not cause cascading failures across the entire application.[6]

But with these advantages comes a significant amount of architectural complexity. In the transition to microservices, software becomes a distributed system and developers need to deal with distributed transactions, service discovery, load balancing, security, observability, configuration management and fault tolerance for their services. It is also much harder to maintain consistency of data across the different databases in such a system than in a centralized monolithic system.[9] Empirical studies in recent years highlight that microservices can enhance scalability, deployment flexibility, and organizational autonomy, but also help to raise operational complexity and demand specialized skills in distributed systems engineering. This means that to get successful adoption, you need to have an organization that is mature, a DevOps capability, automation infrastructure, and a complete monitoring mechanism. Recent research studies have been advocating for the use of microservices only if their architectural benefits are greater than the extra operational complexity.[10]

2.4 Scalability Analysis

Scalability is one of the most appreciated quality attributes of enterprise software systems as it is the ability of the system to perform effectively, given increases in workload. With the growing number of users, transactions, and data that organizations encounter regularly, scalable architectures are crucial to maintaining business continuity and customer satisfaction. There are basically two types of software scalability: vertical scaling and horizontal scaling. Vertical scaling: improving the computational power by upgrading hardware resources, horizontal scaling: distributing the load among multiple servers or service instances. Many modern cloud-based applications are horizontally scalable as they provide more flexibility, fault tolerance, and cost savings. Many modern cloud-based applications are horizontally scalable, which is preferable for flexibility, fault tolerance, and cost savings.[11] The scalability approach of monolithic and microservices architecture is pretty different. Scaling for monolithic systems usually involves replicating the entire application even if only a portion of it is experiencing greater traffic. This can result in the wastage of resources and unnecessary investment in infrastructure. Furthermore, if there are performance issues in any of a module's components, the whole application can become less responsive.[12]

Unlike the microservices architecture, on the other hand, the services in the system can be scaled independently, based on their load, with every service being replicated on its own. This fine-grained scaling mechanism optimizes the allocation of resources, facilitates dynamic scaling based on workloads, and ensures improved application responsiveness when dealing with varying traffic loads. Container orchestration platforms also take care of scaling decisions for users using mechanisms like auto-scaling, health monitoring, and load balancing further automates

the process.[13] While microservices offer great scalability, researchers warn against judging scalability by deployment. The scalability performance encompasses several performance indicators: throughput, response time, latency, resource utilization, fault recovery time and service availability. In addition, the communication overhead produced by distributed systems can cancel out scalability benefits for inappropriate service decomposition.[4] Thus, modern empirical studies indicate that architecture is not only important, but that the quality of system design, the nature of the workload, configuration of the infrastructure and the way in which it is operated by the organization also play a role in determining the scalability of the architecture.[14]

2.5 Maintainability Analysis

Another important software quality attribute is Maintainability, which is the ability by which software can be changed, corrected, enhanced, tested and adapted during its operational life. Enterprise software systems are a dynamic platform that grows and evolves to meet business needs, regulatory changes, new technologies, and security threats. Therefore, maintainability has a key impact on the costs and productivity of the organization over the long term.[11] In monolithic applications, maintainability tends to be good in the early stages of software development, as the code is all in one place and the deployment environment is uniform. Application logic can be easily followed, debugging can be easily done and extensive testing can be done in one system. As applications grow, however, more and more code becomes dependent on one another and everything gets closer together, making software changes harder. Incorporating changes into one module often involves a lot of regression testing throughout the application, which slows development and adds to maintenance work. Modifications to a module typically need to be regression tested throughout the application, which slows down development and adds to maintenance.[12] Many of these limitations can be overcome with modular decomposition in the microservices architecture. Independent services minimize coupling, so that each development team can change, deploy and test services without impacting other services. This independence supports continuous integration and continuous deployment (CI/CD), reduces release cycles, and increases organization's agility in responding to evolving business needs. Plus, smaller codebases are easier to comprehend, refactor and maintain.[4]

While these are great benefits, the challenge of maintainability in microservices is not limited to source code management. Because microservices are distributed, you will have to deal with other maintenance tasks like service orchestration, API versioning, distributed logging, monitoring, security management and dependency coordination. Therefore, modern tools and organization are necessary for maintaining a microservices ecosystem to avoid the growing complexity in the operation.[6] There is a recent body of systematic literature reviews that have found that more than one metric should be used for assessing maintainability, such as coupling, cohesion, modularity, change impact, deployment effort, code complexity, technical debt, and testing effort. Current research has already shown that microservices tend to be more maintainable over time for large enterprise applications, while monolithic architectures are more maintainable for smaller systems where the functional requirements do not change often, and the organizational structure is not particularly complex.[9]

3. Problem Statement

Today, enterprise software systems face the challenges of continuous change of the business landscape and cloud-native computing, and must be capable of high scalability, continuous evolution and efficient maintenance. As a result, software architects often have to choose between different architectural styles, and two predominant styles have emerged: the monolithic and the microservices. While microservices architectures are more modular, can be deployed independently and are more scalable, monolithic architectures are simpler to develop, deploy and manage in a centralized manner. Though these architectural paradigms are widely used, choosing one of them is still a challenging decision since each of these paradigms has its own merits and demerits for different software quality characteristics.

The traits of monolithic and microservices architectures have been studied in recent years, but the majority of research has focused on

studying each software quality attribute by itself rather than as a group. For instance, recent systematic literature reviews were mainly on scalability aspects of microservices like auto scaling, workload management, and resource optimization, while not addressing the implications on long-term maintainability. In the same way, empirical migration studies tend to evaluate the improvement in performance by considering metrics like response time, throughput and error rates, and offer minimal evaluation of maintainability characteristics like modularity, coupling, technical debt and architectural evolution. Because of this, there is no comprehensive knowledge of the effects of scalability improvements on maintainability, and no evidence of negative interactions between architectural decisions made for one quality attribute and another.

This disorganized evaluation can be a major challenge for enterprise organizations. Architectural decisions are rarely influenced by single quality attributes and instead come as a result of a number of interdependent quality attributes. If neither scalability nor maintainability is considered during the design of software architecture, software architects and decision makers do not have empirical evidence to help them select the most suitable software architecture for both operational efficiency and software evolution. Thus, organizations can select architectural solutions that might reflect industry trends or that offer only a single benefit, but not because they have been well-studied to account for the entire architectural landscape. As such, organizations can choose an architectural solution that may be aligned with an industry trend or that may prove to be a single benefit solution, but not because architects have studied the issue thoroughly and know what the architectural trade-offs are.

Thus, an empirical study is needed that can assess the scalability and maintainability of enterprise architectures for both monolithic and microservices architectures. This research combines both of these qualities in a single comparative analysis to give a more holistic understanding of the architectural trade-offs of each approach. The results are anticipated to facilitate evidence-based architectural decision making as organizations will be able to choose a software architecture that meets both current performance needs and software sustainability and adaptability, and can be maintained over time.

4. Research Methodology

To make a comparative analysis of the monolithic and microservices architectures, this work uses a systematic secondary data analysis methodology applied to the field of scalable software design. The research methodology involves a multi-stage literature review process. A detailed search was done initially in the main academic databases, industry publications and conference proceedings. The following key terms were used to find appropriate peer-reviewed articles, empirical studies and technical reports: microservices architecture, monolithic architecture, software scalability and architectural comparison, spanning from 2015 till the present date. To identify the most suitable literature for the current study, a strict screening process was implemented, with pre-defined inclusion criteria that highlight studies where a comparative evaluation, empirical performance data and/or a scalability analysis were included, and exclusion criteria to exclude publications without methodological rigor or with relevance to other contexts. The literature was then critically analyzed and data were gathered about each of the performance metrics (e.g. response time, throughput), maintainability factors, deployment complexity, resource usage and fault isolation. These data were then consolidated and organized thematically to highlight several features, trade-offs and best practice for every architecture paradigm. The secondary research method is to collect information from multiple sources, which can give a “whole-grain” and evidence-based perspective for developing actionable results for software architects and developers to consider when working on scalable system architectural options.

4.1 Monolithic and Microservices Architectures

There are two more popular software architectures—monolithic and microservices—that are becoming more popular. To build scalable and maintainable software systems, it is necessary to have knowledge about their architecture, advantages and disadvantages.

Monolithic Architecture

The components of an application are all put together into a single code base. This is just a few of the features that are incorporated into the user interface, business logic, and data access layers. They are all integrated and implemented as an integrated unit. The holistic approach simplifies development and deployment as all components are contained within a single platform.

Advantages

Simplified Testing and Debugging: Codebase is centralized, making debugging easier and end-to-end testing more simple.

Single Codebase, Simplified Development and Implementation: The development process is eased by keeping a single codebase, and application deployment requires just a single executable file or directory.

Performance: This is due to communications being done within the same process, and the latency may be reduced and working with the same code base could be beneficial.

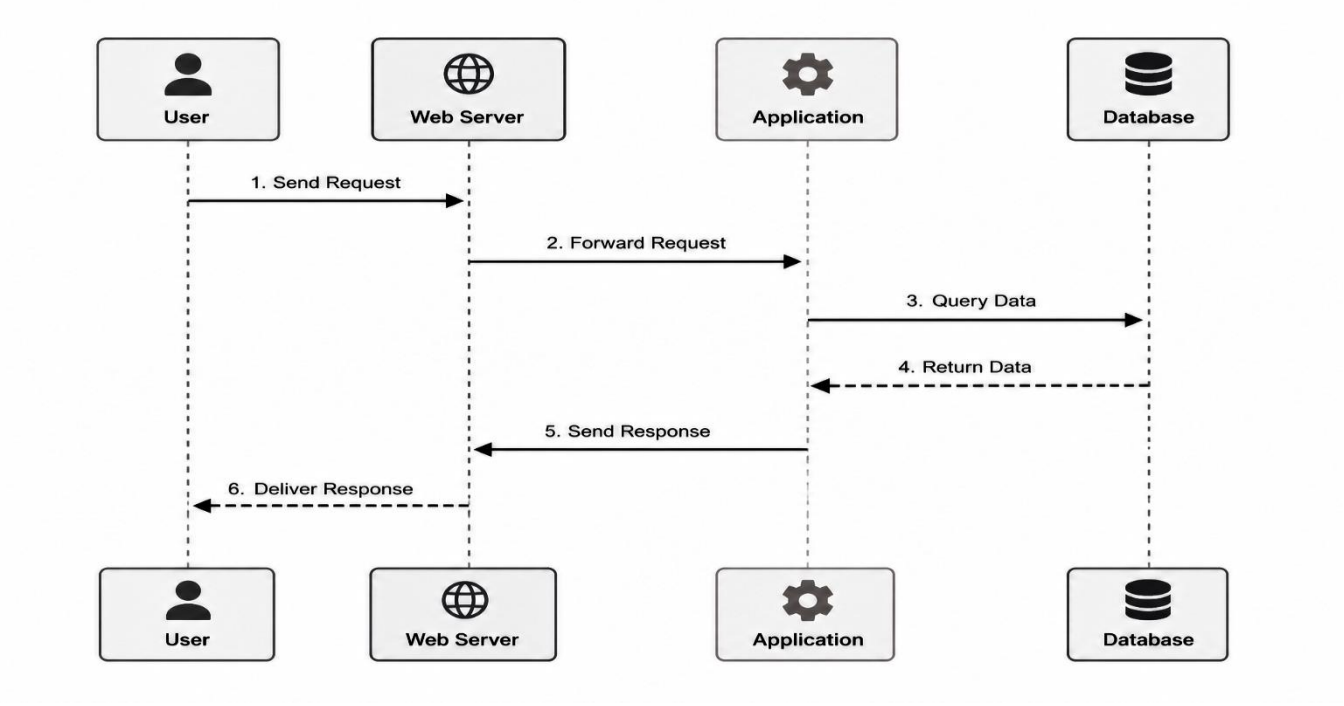
Challenges

Scalability Constraints: Sometimes, when a program is monolithic, it can be hard to scale up the program in order to add new components.

Red deployment: If changes or updates need to be made, the entire program should be redeployed, possibly delaying changes and prolonging deployment cycles.

Growing Codebase Complexity: Over time, the code base can become quite large and complex, making it challenging to maintain and understand.

Figure 1:



Microservices Architecture

Using a microservices architecture, an application is broken down into several tiny, independently deployable services, each in charge of a distinct business function. These are flexible, resilient and services can be designed, deployed, scaled and well-defined and communicated through well-defined APIs.

Advantages

Enhanced Scalability: Services can be scaled independently based on workload, ensuring optimal performance and efficient use of resources.

The development teams enjoy flexibility of choice and a level of maintainability when picking the technologies, they feel are particularly appropriate for the services they are developing, as well as updating, modifying and maintaining.

Fault Isolation and System Resilience: Failures in one service are isolated and doesn't affect other

services in the system; improves reliability, flexibility.

Challenges

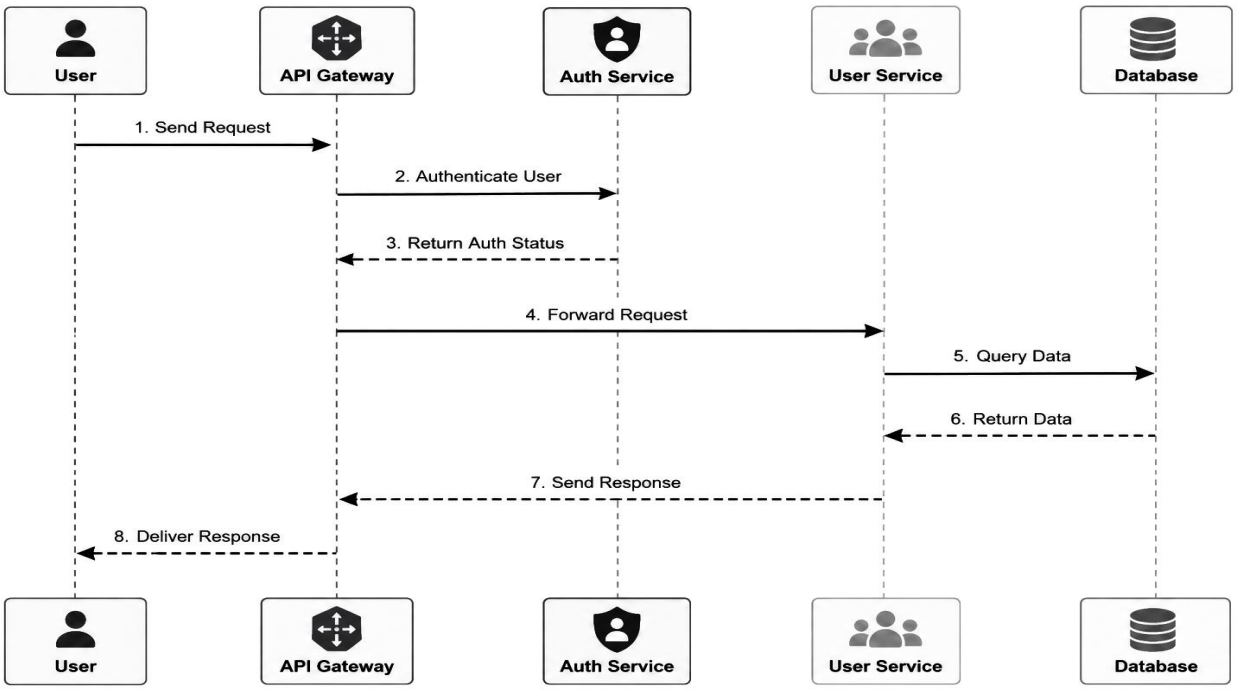
Requirements for improved Complexity in Communication: Consistency maintenance, transaction management and messaging coordination with services can be complicated and need for an extensive coordination system.

System Integrity: Services are independent and careful monitoring and advanced deployment must be considered to achieve the integrity of the system as a whole.

Potential for Distributed System Issues: There may be distributed system problems. Problems can occur with load balancing, serialization and latency can be an issue, making architecture considerations important.

The microservices design pattern has the API Gateway as a mediator that routes calls to the services such as AUTH Service and User Service. Services are individually active on the network, and therefore have additional latency over that of a monolithic approach.

Figure 2:



4.2 Comparative Analysis of Previous Studies

With today's rapidly changing enterprise software systems, the modern software architectural paradigms have had a significant impact. Organizations have come to demand software systems that can support continuous business growth, fast deployment cycles, high availability, and effective maintenance in a cloud-native environment. Therefore, choosing the right software architecture has emerged as a critical choice that directly impacts software quality attributes such as scalability, maintainability, performance, reliability, and operational efficiency. In software engineering, there are several different types of architecture, but the two most popular ones are Monolithic and Microservices architectures applied to the development of enterprise applications. Recent literature shows that while microservices are gaining popularity due to their scalability and deployment flexibility, there are still some benefits in monolithic architectures for those who need lower operational complexity and centralized management in their systems. This has been responsible for current research oriented to discovering the architectural cost–benefit or compromises to be made in different organizational situations, but not to determining "which is better?". [15], [16]

The trend of the day isn't necessarily the optimum

solution for software architecture - the decisions should be driven by the changing of the needs of the organizations, the complexity of the application, the experience of the developers, and the likely evolution of the system. Benjamin [15] explains that in today's enterprise, the applications will need architectures that can support continuous integration, continuous deployment, cloud-native infrastructure and rapid feature delivery. To help address these requirements, microservices architecture takes an approach of 'loosely coupled', dividing applications into a series of loosely coupled services, which can be developed, deployed and scaled independently. However, Kambhammettu [17] argues that for some organizations, their lines of business are less dynamic, teams smaller and operational resources less, thus making monolithic systems still useful. This has occurred enough times in the architectural world to demonstrate that not every architectural preference is an engineering fact and choice is a contextual decision.

The different software systems structure is one of the major differences that exist between various pieces of literature. Monolithic architecture is in a single deployable application which contains presentation, business logic and data access components. All modules coexist in the same runtime environment, and communicate directly through function calls, which makes the software development easier. The centralized architecture results in lesser amount of communication overhead, facilitating easier debugging, and integration testing. However, as applications increase, software flexibility over time will decrease, and the increased software coupling of modules will increase maintenance costs. Migrating one subsystem may entail other subsystems wanting to be recompiled, retested, redeployed to new hardware, or new locations on the same or different hardware, which can be costly and time consuming [18] [17].

In contrast to the philosophy of microservices architecture, application organization in microservices turns into totally different: it is broken into individual providers, customized around a particular business operate. Every service has its own business logic, database, deployment pipeline, and communication interface via REST API or gRPC, or some other asynchronous messaging system. This modular decomposition allows independent deployment, technology heterogeneity, fault isolation and decentralized software evolution as emphasized by Benjamin [15]. Likewise, Wahyudin et al. [18] report that service-level isolation makes software more flexible since service developers can modify, update and deploy services without affecting the other services. These qualities are a major contributor to organizational agility, especially in organizations going down the DevOps and continuous delivery route. However, all the reviewed studies agree that distributed architectures significantly complicate the infrastructure by adding service discovery, API gateways, distributed tracing, centralized logging, orchestration platforms like Kubernetes, and containerization technologies like Docker, [15], [18], [17].

Out of all the investigated studies, scalability is the most common quality attribute and one of the biggest motivations for using microservices architecture. Gurung et al. [16] found that scalability research is the predominant research area in microservices engineering by conducting a systematic literature review of 55 primary studies. They list the main research areas for better service scalability as auto scaling, container orchestration, workload prediction and machine learning for resource management. While most monolithic systems need to replicate the entire application as demand grows, microservices allow them to scale horizontally for specific services that are being used more intensively. This allows for more efficient use of computational resources, optimizing infrastructure utilization and cloud operational costs.

Additionally, the empirical results reported by Wahyudin et al. [18] support these observations. They have done a performance comparison between the Laravel based monolithic architecture and the Golang gRPC based microservices architecture which shows that there are several performance improvements to be achieved from migrating to a microservices architecture. In particular, the migrated system showed a reduced error rate, higher throughput and lower response time in the load testing, soak testing, and stress testing. The results give quantitative evidence to support the argument that independently deployable services can support scalability at increasing workloads. The authors are also aware

of the fact that these performance enhancements must involve significant architectural redesign, the use of container technologies, API gateways, service orchestration mechanisms and sophisticated communication protocols, which makes implementations more challenging.

While scalability is definitely an advantage of microservices, the literature reviewed reveals that maintainability is a more complex trade-off. Developers working in a single codebase, single database, and single tech stack make for significant maintainability benefits in the early stages of software development with traditional monolithic systems. This controls application behavior so that software maintenance tasks such as dependency management, integration testing and debugging are much easier. These features have been highlighted by Kambhammettu [17] as lowering software complexity for the development teams and making the software governance and operational management much easier. As programs grow larger, the maintainability slowly decreases. As the code grows larger, it starts to accumulate technical debt, introduces more inter-module dependencies, and decreases the modularity of software, making it more and more difficult and costly to modify in the future.

The problem with these drawbacks is addressed by microservices architecture by breaking down the monolith into smaller units and making every unit own its services. A major observation Benjamin [15] makes is that every service adheres to the Single Responsibility Principle, having one business capability within its distinct service boundaries. This decomposition enhances the modularity of the software, enables the software to be maintained independently and ensures that different teams can develop the software at the same time without interfering with each other's work. Furthermore, independent deployment pipelines allow businesses to release updates to software with greater frequency and in response to business needs. However, there are consistent findings in the literature that maintainability in distributed systems is not limited to source code management. Rather, developers need to have to deal with service orchestration platforms, network communication protocols, authentication, distributed monitoring, centralized logging, service discovery frameworks, and inter-service compatibility all at the same time. This means that the source-code maintainability goes up, while the operational maintainability goes down significantly [15], [18], [16].

One of the main lines of research coming from the latest literature is the realization that architectural decisions should not be made in a binary fashion. Rather, there has been a trend toward hybrid approaches that combine the simplicity of monolithic systems with modularity of microservices. According to Al-Qora'n and Ahmad [19] the Modular Monolith Architecture (MMA) is a potential intermediate solution in cloud-native environments. They have performed a systematic literature review and found that modular monoliths maintain centralized deployment, contain modular boundaries, embrace Domain-Driven Design (DDD), and enhance separation of concerns. In comparison to microservices, modular monoliths have significantly reduced orchestration, deployment and operational costs, as well as increased maintainability over a monolith application. Some organizations have started reconsidering their “over-sliced” services deployments on a large scale as it can further complicate the business without certainly delivering more of it.

An interesting development in the research of software architectures today is the emergence of modular monoliths. The researchers are now looking towards balancing the degree of modularity with ease of maintenance, scalability and operational complexity instead of demanding more and more granular services. This perspective is similar to Kambhammettu [17] who stablished the relationship between architecture as if it was on a trajectory rather than oppositional. The successful enterprise systems are thus configured with the organization's means and the maturity of the software, as well as the nature of the workload and how it is to be maintained over time; they are not just about the latest enterprise web service fad, microservices.

Weirdly, the studies looked at consistently go beyond the complexity of deployment, the management of operational software, the resilience of the system, the organizational structure, and the long-term evolutions of the software, all within the architectural choice made between monolithic or microservices

architectures in addition to the scalability and maintainability. While microservices offer many benefits to large, enterprise applications, it comes with a lot of operational complexity. But recent studies and research is now evolving towards a more complex and sophisticated analysis of the pros and cons and costs involved in architecture rather than just taking the "seven microservices" dogma for granted as an inevitability of enterprise software development.

One of the most important factors distinct between both architectures is as to their deployment and operational management. When the application is monolithic, it is comparatively still easy to deploy it. Use one code repo, one deployment pipeline, common configuration and consistent database. This simplicity reduces operating expenses and allows for a greater ease of testing, version control, rollback and monitoring. These traits seem to be why monocultures are readily-suited for startups, small dev teams—anything other than a DevOps company, Kambhammettu [17] argues. As the enterprise applications grow, however, simplicity of deployment starts to pose problems, as minor changes require rebuilding, testing and deploying the entire application, putting this more at risk and lengthening release cycles.

In the case of monolithic architecture, however, it is not possible to deploy individual services without disrupting other services as is possible with microservices architecture. This deployment independence, Benjamin says, will offer development agility by making development practices such as CI/CD easier. Any changes to business services by each individual development team would not affect other application modules. Likewise, Wahyudin et al. [18] have shown that the deployment of microservices can be significantly improved with the use of Docker containerization, Kubernetes orchestration, API gateways and automated deployment pipelines. These enable the ability to flexibly deploy these technologies in the cloud and to dynamically manage services. However, all of the studies agree that there is significant operational complexity when deployments are independent, as they need to coordinate many services, distributed configurations, authentication mechanisms, service discovery platforms, monitoring systems, and network communication protocols.

Another major architectural trade-off that emerged from the literature was fault-tolerance and system resilience. With monolithic systems, application components are run in the same runtime environment and failures of one critical component can have a negative impact on the entire application. All modules are connected tightly and software problems often spill over functional lines, which makes it more likely that total system failures occur. This centralized dependency structure also makes fault isolation difficult as the root cause of failures can be hard to determine, sometimes requiring examination of the entire application. As software becomes more complex, maintaining high system availability becomes more difficult.

The microservices architecture overcomes this issue by isolating each service. Each service runs in isolation, and, therefore, failures typically don't impact the other services in the application. Benjamin [15] explains several architectural patterns that help to ensure resilience, such as circuit breaker, load balancing, service discovery, redundancy, and container orchestration. In addition, Wahyudin et al. [18] show how isolated services can help reduce the amount of errors when performing stress testing since a single service failure does not necessarily prevent the overall system function. However, due to the distributed nature of microservices, it also leads to new reliability issues like network delay, message loss, distributed transactions, inter-service dependency management, etc. Thus, while microservices help to isolate faults, they also need to be monitored, observed and recovered with advanced mechanisms, which adds complexity to the operations.

An additional theme that runs throughout the reviewed studies is related to organizational issues. The architecture of software affects not only software implementation, but also team organization, teamwork and software delivery process. Traditionally, monolithic architectures provide for a central development team sharing a single codebase. The model works well for small development teams, but can become inefficient in larger teams due to the possibility of multiple developers modifying different parts of the same module at the same time, leading to conflicts and delays in development. As software changes, tightly coupled parts hinder development

autonomy and restrict parallel feature implementation.

Microservices Architecture aims to support the decentralized organizational model based on business capabilities. Each team takes responsibility for the delivery of specific services so that they can be developed, tested, deployed and maintained independently. Organizational alignment with software architecture is a consequence of Conway's Law, which states that 'software reflects organization'. According to Benjamin [15] such autonomy greatly enhances development productivity and speeds up the software evolution process. But for this organizational agility, the teams need to have some level of DevOps maturity, some level of governance and governance policies, comprehensive documentation and some level of inter-team coordination. Otherwise, these organizational skills can lead to inconsistent operations, to two or more jobs or operational risks with the independence of service.

The reviewed literature also highlights the growing importance of the cloud-based technologies during decisions making for architecture. Today, more and more microservices environments are based on Kubernetes, Docker, API gateways, Service Meshes, distributed logging, centralized monitoring, and automatic scaling. Gurung et al., [16] have detected that the primary research area of today's literature on microservices is the one of auto scaling, where machine learning techniques are most commonly applied to predict workload variations and allocate the right amount of resources. Their systematic review shows that future research on scalability is moving beyond static scalability to a framework of intelligent, adaptive auto scaling models that are able to calculate the balancing between performance, infrastructure costs and energy efficiency. The results indicate that scalability is not simply a horizontal replication concept – it requires intelligent orchestration approaches, that are dynamically adaptive to changing enterprise loads.

Nevertheless, despite all of these technologies, the aforementioned studies all raise the red flag that microservices don't necessarily outperform monolithic systems in all situations. Wahyudin et al. [18] demonstrate that microservices' performance—response time, throughput and error rate—is superior to that of monolithic applications at an extremely high price, which involves redesigning the architecture, establishing communication infrastructure, implementing the container orchestration, and automation of operations. Likewise, Benjamin [15] highlights the benefits of independent scalability and deployment with the challenges of distributed data consistency, service coordination and security management. As a result of these findings, the benefits of microservices will be apparent only when the organization is technically capable, the software ecosystem is developed and the infrastructure is mature, and the organization can effectively manage a distributed software ecosystem.

One of the key advancements that have come from modern literature is the growing acknowledgment of Modular Monolith Architecture (MMA) as a different paradigm of architecture. According to Al-Qora'n and Ahmad [19] MMA combines the centralized deployment capabilities of monolithic systems and the modularity that has been traditionally used in microservices. Maintainability, simplified deployment, reduced orchestration overhead and improved modular boundaries are identified by their systematic review as the main drivers for adopting modular monoliths. In addition, the authors note that an emerging industry trend is the departure from highly fragmented microservices ecosystems as the many services can add to operational complexity and infrastructure expenses. The literature is increasingly supportive of the notion of an architectural transition to microservices from monoliths, rather than a dichotomy of monoliths vs microservices; when the business needs dictate it, the goal is to avoid a deployment transition from a monolith to a distributed architecture by viewing software architecture as an evolutionary process that involves the creation of incremental steps that are done at the right time.

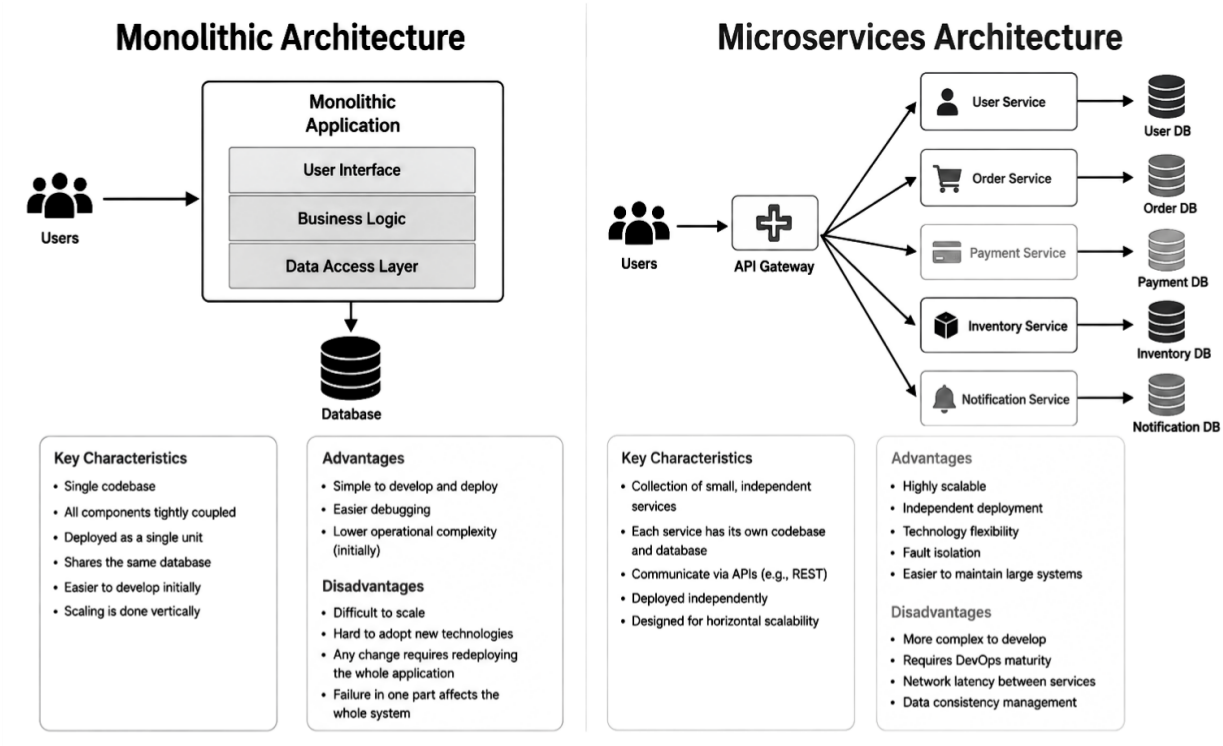
As a group, the studies reviewed show that architectural selection is a multi-dimensional decision that goes beyond software performance, technical, organizational, and operational factors play a role. For modestly complex applications that involve centralized development, less stringent infrastructure needs, and predictable business requirements, the benefits of monolithic

architecture remain strong. It is deployed with minimal effort and managed from a single central point, making it an ideal choice for organizations that are focused on quick product development and reduced maintenance costs when evolving their systems at an early stage. The other way round, microservices architecture gains more and more value the larger, more complex and more variable the workload of enterprise applications becomes. Large organizations with the ability to support complex cloud-native infrastructures enjoying independent scalability, modular service ownership, deployment autonomy, and enhanced fault isolation are enjoying significant benefits in the longer term. These benefits, however, come at the price of increased distributed system complexity, higher operational cost and increased demand for DevOps expertise.

While the literature reviewed has a wealth of comparisons of the architectural characteristics, there are some areas of research that remain. Current research typically focuses on scalability, maintainability, migration approaches or performance separately, without considering the interplay among these quality aspects in actual enterprise settings. Furthermore, most empirical assessments are restricted to a few case studies or a single performance metric (response time, throughput, resource utilization, etc.) and few have considered evaluating multiple maintainability metrics alongside multiple architectural evolution, technical debt and operational cost metrics in a single study. Likewise, while modular monolith architecture has become a viable option in recent years, there is not much empirical evidence that has been done to compare against traditional monoliths and microservices. Thus, more empirical research is needed to create general evaluation frameworks that allow the evaluation of architectural trade-offs with respect to multiple quality attributes in modern enterprise environments.

This research tackles these shortcomings by examining the monolithic vs microservices architectures from a holistic point of view that combines scalability and maintainability. In contrast to the prior work that focuses on each of these quality attributes in isolation; the present study seeks to investigate the inter-relationship between these quality attributes in enterprise software environment and thus offers a comprehensive view of architectural trade-offs and evidence to guide software architectural decision-making in the current software enterprises.

Figure 3:



4.3 Empirical Evidence and Case Studies

The benefits of microservices in terms of scalability have been proved in empirical studies. For example, re-architecting a monolithic system to a microservices architecture had a positive effect on scalability in a case study of moving a mission-critical system to Danske Bank. The microservices paradigm changed the way software is designed, conceived and perceived, thereby improving the scalability result.

In another study, the impact of splitting monolithic application into microservices was explored. Additionally, the findings showed that the microservices design had better results in software modularity metrics than the other designs, while consuming less memory and CPU. This suggests microservices enhance scalability and more effective resource use.

Table 1:

Test Scenario	Monolithic Response Time	Microservices Response Time	Monolithic Throughput	Microservices Throughput
Single User Load	200ms	180ms	100 req/s	110 req/s
100 Concurrent Users	2s	1.8s	50 req/s	55 req/s
1000 Concurrent Users	20s	15s	10 req/s	12 req/s

A benchmarking table is a systematic and structured representation of data that can be used to assess and compare the performance of various systems, processes or products with respect to agreed standards or reference points. These tables also have a pivotal role in performance analysis as it helps identify strengths, weaknesses and areas for improvement. They aid empirical evidence-based decision making, by providing easy-to-understand and comparable empirical data. Despite its inclusion at the start to relevance from the software circumstances, scalability remains one of the most critical aspects of software architecture design that should influence the performance, user satisfaction and company growth of the system. Monolithic architectures can do the job for applications which do not require high scalability and have relatively stable workloads (Kothapalli, 2021). However, for those apps that need to scale to a significant degree and are likely to change significantly over time, microservices architectures are more flexible and efficient. Microservices operate independently of each other and scale them to fine granularity, thereby adjusting the existing behavior of systems according to workload demands and ensuring its stability. This is "focuses" scalability – ensures optimum performance without wasting resources. Therefore, consider the scalability requirements, system complexities and future growth plans done carefully, when looking at a monolithic vs microservices architecture. A greater insight into the advantages and disadvantages of each paradigm allows software architects and software developers to design systems that satisfy the current needs as well as remain scalable, flexible and sustainable.

5. Results and Data Analysis

5.1 Analyze for scalability synthesis.

The systematic secondary data-analysis method clearly brings out the operational limits of architectural paradigms under different concurrent workloads. The monolithic architecture and microservices architecture show different scaling behaviors in the test scenarios based on the empirical performance data extracted: ·

Single User Load: In baseline they both perform well. The response times at the microservices configuration are a slightly optimized 180ms and throughput of 110 req/s, while the response time of the monolithic architecture is 200ms and throughput is 100 req/s. This verifies that in isolated cases of simple workloads, the inter-module communication in one process incurs very little processing overhead.

100 Concurrent Users: The beginning of resource degradation is seen as the concurrency approaches a moderate level. The monolithic system has a latency of 2s and a throughput of 50 req/s. At the same time, the microservices design

achieves a response time of 1.8s and throughput of 55 req/s. It becomes restrictive whenever the centralized monolithic codebase gets its scalability constraints as the number of concurrent users approaches 1000. The response time reaches 20s for the monolith, and its throughput falls to 10 req/s because of the need to have a complete copy of the whole unified system rather than a single point of failure. On the other hand, with microservices the response time degradation is capped at 15s with a higher throughput of 12 req/s. These trends are reinforced by the findings in the various industrial case studies, including the one on relocation of a mission critical system at Danske Bank. The direct benefit of re-implementing the monolithic framework as independent services is high load scalability improvements and the assurance of fine-grained resource allocation.

5.2 Evaluation of Maintainability Synthesis

The qualitative information collected from literature reveals that there is an inverse relationship between the structural maintainability and the raw measures of performance:

Monolithic Modular Deterioration: At first, the centralized code base aids the improvement and also internal debugging due to all components being provided on one platform. However, as enterprise software grows UI starts to become more dependent on business logic and accessing the data stores, making the code base more complex. As each subsystem change needs an entire deployment cycle, it is bound to restrict flexibility for evolution.

Microservices granular maintenance is a strict modularity requirement: Application's ideal design break is into independent parts, each of which is connected to a different business service (AUTH or User services).

5.3 Integrated Trade-off Analysis

The results obtained by this synthesis show a clear, concurrent link between scalability and maintainability, directly aimed at the main core objectives of the present research:

Table 2:

Architectural Attribute	Monolithic Architecture	Microservices Architecture
Low-Load Performance	High process efficiency; lower latency function calls.	Network communication via API gateways introduces inherent processing delay.
High-Load Scalability	Rigid vertical or horizontal duplication constraints.	Granular, independent service scaling based on dynamic demand.
Code Base Modularity	Centralized dependency leading to structural complexity.	High structural modularity; isolated fault boundaries.
Operational Overhead	Simplified testing, deployment, and localized debugging.	Advanced tracking overhead; complex distributed data consistency.

The evaluation points out that the choice of architecture should depend on the workload volatility and the organizational maturity with respect to DevOps. In environments where the application is stable and centralized and simplicity of operation is a key requirement, the monolithic approach continues to be effective. When software is expected to be maintained for a long time, faults need to be isolated, and extensive workload elasticity is desired, the microservices architecture offers a more sustainable structural framework than the monolithic system even in the face of distributed system overhead.

6. Conclusion and Future Work

6.1. Conclusion

This research compared the architecture trade-offs between monolithic and microservices architecture, incorporating scalability and maintainability aspects. The synthesized results showed that both architectures have similar

performance under low workloads: monolithic architecture response time is 200ms and microservices architecture is 180ms. But when the load grew to 100 and 1000 users, the microservices architecture kept its response times and throughput low, proving its ability to scale effectively under enterprise conditions. The maintainability analysis has shown that monolithic architecture makes initial development, testing and deployment of the application easier because it is a single codebase, but as the application becomes more complex, it is more difficult to maintain. Microservices, on the other hand, make it easier to maintain the system over time by breaking it up into smaller services that can be deployed and maintained separately, but adds to the operational complexity with regard to communication and service orchestration between the services. The results address directly the research gap addressing the needs of giving an integrated evaluation of the scalability and maintainability, as well as support for the research objectives and guidance for taking evidence-based decisions for architectural decisions in enterprise software systems.

6.2. Future Work

Other work needs to be done to further expand this comparison, with the support of empirical benchmarks that have been crafted in a controlled manner for cloud-like environments that rely on container orchestration like Kubernetes, so as to verify the architectural behaviors for actual deployments. Future quantitative analysis of the Modular Monolith Architecture (MMA) is also proposed to evaluate the feasibility of incorporating this architecture as a hybrid variety of collective microservices and monolithic architectures with scalability and simplicity/ongoing support of operations advantages.

Conflict of Interest

The authors showed no conflict of interest.

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